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HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

PREFACE

Mr. M. M. Culp, former Chief of the Design Branch, suggested the Design Unit make a study of a steepened riprap channel to obtain gradient control. The resulting investigation led Mr. Paul D. Doubt, former Head of the Design Unit, to conceive and develop the riprap gradient control structure presented in this technical release. The first version of a computer program to determine the dimensions and parameters associated with the design of this riprap structure and portions of a preliminary draft of this technical release were written by Mr. Doubt.

A draft of this technical release dated July 14, 1975, was circulated through the Engineering Division and sent to the Engineering and Watershed Planning Unit Design Engineers for review and comment.

A publication is being prepared which will contain the necessary charts for the graphical solution of parameters used in the design of a limited class of riprap structures.

This technical release was prepared by Mr. H. J. Goon with the assistance of Mr. John A. Brevard, both of the Design Unit, Design Branch, Engineering Division, Hyattsville, Maryland.

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HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

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NOMENCLATURE

This technical release uses, insofar as possible, nomenclature which commonly appears in hydraulic literature. However, when nomenclature involves lower case letters, subscripts, and Greek letters, difficulties are encountered in presenting, describing, and interpreting computer input and output. Therefore, sometimes two symbols have the same meaning; one is used in the text and the other is used in describing computer input and output data. The symbols used for input and output data are also defined in the "Computer Program" section of this technical release.

a ≡ Flow area, ft^2

a_a ≡ Average flow area, ft^2

a_c ≡ Flow area corresponding to critical depth, d_c, ft^2

a_n ≡ Flow area corresponding to normal depth, d_n, ft^2

b ≡ Bottom width of trapezoidal section, ft

b_a ≡ Average width of channel, ft

b_j ≡ Bottom width of the transition at any section j, ft

BS ≡ Bottom width at the ends of the riprap structure, ft

BU ≡ Bottom width of the prismatic channel of riprap structure, ft

C_{50} = C50 ≡ Coefficient relating critical tractive stress to riprap D_{50} size, $\tau_{bc} = C_{50} D_{50}$

C_n = CN ≡ Coefficient relating Manning's n to riprap D_{50} size, $n = C_n \left[D_{50} \right]^{EXPN}$

CONV ≡ Rate of convergence of the bottom width of the upstream transition, ft/ft

CS $= \frac{s_n}{s_c}$ ≡ Maximum allowable ratio of bottom slope to critical slope

CSU $= \frac{SN}{SC}$ ≡ Ratio of bottom slope to critical slope used in the design of a particular riprap structure

CTAUB ≡ A coefficient used to determine the maximum tractive stress along the boundary of the riprap lining on the bottom of the prismatic channel

CTAUS ≡ A coefficient used to determine the maximum tractive stress along the boundary of the riprap lining on the side slope of the prismatic channel

$C_{\tau b}$ $= \frac{\tau_{bm}}{\tau_{av}}$ ≡ Ratio of maximum tractive stress on bottom of channel to average tractive stress

$C_{\tau s}$ $= \frac{\tau_{sm}}{\tau_{av}}$ ≡ Ratio of maximum tractive stress on side slope of channel to average tractive stress

d ≡ Depth of flow, ft

D_{50} = D50 ≡ Size of rock in riprap of which 50 percent by weight is finer, ft

D50U ≡ The D_{50} size of riprap used in the design of a particular riprap structure, ft

d_c ≡ Critical depth corresponding to design discharge, Q, ft

DC ≡ Critical depth corresponding to design discharge, Q, in the prismatic channel of riprap structure, ft

DIV ≡ Rate of divergence of the bottom width of the downstream transition, ft/ft

d_n ≡ Normal depth corresponding to design discharge, Q, ft

DN ≡ Normal depth corresponding to the design discharge, Q, in the prismatic channel of riprap structure, ft

$d_{n,d}$ ≡ Normal depth in the downstream channel, ft

$d_{n,u}$ ≡ Normal depth in the upstream channel, ft

DS ≡ Depth of flow corresponding to the design discharge, Q, at the ends of the riprap structure, ft

EXPN ≡ Value of the exponent in the equation for computing Manning's roughness coefficient, $n = C_n [D_{50}]^{EXPN}$

F ≡ Resultant of horizontal forces acting on the body of moving water, lb

F_1 ≡ Resultant of hydrostatic pressures acting at Section 1, lb

F_2 ≡ Resultant of hydrostatic pressures acting at Section 2, lb

F_f ≡ Total frictional force, lb

FS ≡ Factor of safety

FSU ≡ Factor of safety used in the design of a particular riprap structure

g ≡ Acceleration of gravity, ft/sec^2

H ≡ Specific energy head corresponding to the design discharge, Q, ft

HC ≡ Critical specific energy head corresponding to the design discharge, Q, ft

h_f ≡ Friction head loss, $\frac{\text{ft-lb}}{\text{lb}}$

HN ≡ Normal specific energy head corresponding to the design discharge, Q, in the prismatic channel of the riprap structure, ft

$$J \equiv \frac{\left[\text{Distance in the transition from any section } j \text{ to section of width BU}\right]}{\text{total length of the transition}}$$

$$K = \frac{\tau_{sc}}{\tau_{bc}} = \sqrt{1 - \frac{\sin^2(\cot^{-1} z)}{\sin^2 \theta}}$$ ≡ Ratio of critical tractive stress on side slope to critical tractive stress on bottom of the trapezoidal channel

$$KPS = \frac{p_n}{s_n}$$ ≡ Ratio of wetted perimeter to bottom slope of the prismatic channel

ℓ ≡ Horizontal length of a portion of a channel, ft

LDT ≡ Length of downstream transition, ft

LPC ≡ Length of prismatic channel, ft

LT ≡ Length of the transition, ft

LUT ≡ Length of upstream transition, ft

M = $\frac{\gamma\, Qdt}{g}$ ≡ mass of body of water between Sections 1 and 2

n = N ≡ Manning's coefficient of roughness

p ≡ Wetted perimeter, ft

p_c ≡ Wetted perimeter corresponding to the critical depth, d_c, ft

p_n ≡ Wetted perimeter corresponding to the normal depth, d_n, ft

Q ≡ Design discharge through the riprap structure, cfs

$Q_{n,d}$ ≡ Normal discharge corresponding to depth, d, cfs

r = RN ≡ Hydraulic radius at normal depth, ft

s ≡ Energy gradient, ft/ft

s_c = SC ≡ Critical slope corresponding to the design discharge, Q, in the prismatic channel of the riprap structure, ft/ft

s_n = SN ≡ Bottom slope of the prismatic channel of the riprap structure and also normal slope corresponding to the design discharge, Q, ft/ft

s_o ≡ Slope of channel bottom, ft/ft

t ≡ Time, sec

TAUBA = $\frac{C50 \times D50U}{FSU}$ ≡ The allowable tractive stress for the riprap lining on the bottom of the prismatic channel, lb/ft^2

TAUBM = (CTAUB)(γ)(RN)(SN) ≡ The maximum tractive stress along the riprap lining on the bottom of the prismatic channel, lb/ft^2

TAUSA = $K \frac{C50 \times D50U}{FSU}$ ≡ The allowable tractive stress for the riprap lining on the side slope of the prismatic channel, lb/ft^2

TAUSM = (CTAUS)(γ)(RN)(SN) ≡ The maximum tractive stress along the riprap lining on the side slope of the prismatic channel, lb/ft^2

T_c ≡ Top width of flow corresponding to critical depth, d_c, ft

THETA = θ ≡ Angle of repose of the riprap, degrees

v ≡ Velocity corresponding to the design discharge, Q, ft/sec

v_a ≡ Average velocity, ft/sec

VN ≡ Velocity at normal depth corresponding to the design discharge, Q, in the prismatic channel of riprap structure, ft/sec

VS ≡ Velocity corresponding to the design discharge, Q, at the ends of the riprap structure, ft/sec

W ≡ Total weight of water between sections, lb

x_c $= \frac{d_c}{b} \equiv$ Ratio of critical depth to bottom width

x_n $= \frac{d_n}{b} \equiv$ Ratio of normal depth to bottom width

z ≡ Side slope of trapezoidal section expressed as a ratio of horizontal to vertical, ft/ft

ZL ≡ Side slope of the left bank at the ends of riprap structure, see SECTION A-A of Figure 1, ft/ft

ZR ≡ Side slope of the right bank (looking downstream) at the ends of riprap structure, ft/ft

ZS ≡ Side slope of trapezoidal section at the ends of riprap structure, ft/ft

ZU ≡ Side slope of the prismatic channel of the riprap structure, ft/ft

γ ≡ Unit weight of water, lb/ft^3

θ = THETA ≡ Angle of repose of the riprap, degrees

τ ≡ Tractive stress, lb/ft^2

τ_{av} $= \gamma rs$ ≡ The average tractive stress, lb/ft^2

τ_{ba} $= \frac{\tau_{bc}}{FS}$ ≡ The allowable tractive stress for the riprap lining on the bottom of the trapezoidal channel, lb/ft^2

τ_{bc} $= C_{50}\ D_{50}$ ≡ The critical tractive stress for the riprap lining on the bottom of the trapezoidal channel, lb/ft^2

τ_{bm} ≡ The maximum tractive stress along the riprap lining on the bottom of the trapezoidal channel, lb/ft^2

τ_{sa} $= K\ \tau_{ba}$ ≡ The allowable tractive stress for the riprap lining on the side slope of the trapezoidal channel, lb/ft^2

τ_{sc} $= K\ \tau_{bc}$ ≡ The critical tractive stress for the riprap lining on the side slope of the trapezoidal channel, lb/ft^2

τ_{sm} ≡ The maximum tractive stress along the riprap lining on the side slope of the trapezoidal channel, lb/ft^2

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HYDRAULIC DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURES

Introduction

In some cases a riprap gradient control structure can be used economically to dissipate excess energy and establish a stable gradient in a channel where the gradient without some such control would be too steep and would cause erosive velocities.

The riprap gradient control structure discussed herein consists of a riprap prismatic channel with a riprap transition at each end (see Figure 1). Its essential feature is that the specific energy of the flow at design discharge is constant throughout the structure and is equal to the specific energy of the flow in the channel immediately upstream and downstream of the structure. Thus, for the design discharge, the dissipation of hydraulic energy in the structure is at the same rate as the energy gain due to the gradient. The structure, which is made steeper and narrower than the adjoining channel upstream and downstream, maximizes energy dissipation.

For brevity, riprap gradient control structures will be referred to in this technical release as riprap structures or simply as structures. All channels and structures considered in this technical release have trapezoidal cross sections and subcritical slopes.

Report 108

The National Cooperative Highway Research Program Report 108[1] entitled "Tentative Design Procedure for Riprap-Lined Channels" presents the analyses of experimental results, development of criteria, and design procedures for the stability of riprap linings. Hereafter, this publication is referred to as Report 108. It contains information useful in the design of trapezoidal channels constructed in noncohesive sand and gravel materials and of riprap linings which form the boundary of channels and gradient control structures. Report 108 also presents criteria and recommendations for riprap layer thicknesses and for required filters. Report 108 states that laboratory experimental studies on linings designed in accordance with its procedures showed the linings did not fail until discharges reached values in excess of the design discharges.

St. Anthony Falls Hydraulic Laboratory Project Report No. 146 entitled "Tentative Design Procedures for Riprap-Lined Channels - Field Evaluation" by Alvin G. Anderson, June, 1973, for National Cooperative Highway Research Program, presents the results of field evaluation studies of four constructed riprap-lined channels designed in accordance with the procedures contained in Report 108. The studies showed that all four channels were performing satisfactorily, and two of the channels were without signs of erosion after having been subjected to discharges that approach the design discharges.

[1] Publication of the Transportation Research Board, National Research Council, National Academy of Sciences - National Academy of Engineering, 1970

Purpose of Technical Release

The purpose of this technical release is to present procedures for the design and proportioning of riprap gradient control structures. These procedures can also be used to obtain a riprap channel design. This technical release also documents the criteria and procedures used in the associated computer program.

Computer Program

A computer program, written in FORTRAN for IBM equipment, determines dimensions and parameters associated with the design of a riprap gradient control structure. The program operates in any of four modes. Mode 1 obtains only the design of a riprap prismatic channel. Modes 2, 3, and 4 obtain the design of a riprap structure including the prismatic channel and both transitions of the structure. Modes 3 and 4 permit greater flexibility of design.

Input and output data information is discussed under the "Computer Program" section. Computer design runs may be obtained by request to

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Federal Center Building
Hyattsville, Maryland 20782.

Riprap Gradient Control Structure

A riprap gradient control structure is a riprap structure consisting of a prismatic channel with a converging inlet transition at the upstream end and a diverging outlet transition at the downstream end of the prismatic channel. The riprap structure as designed should have essentially a straight alignment as shown in Figure 1.

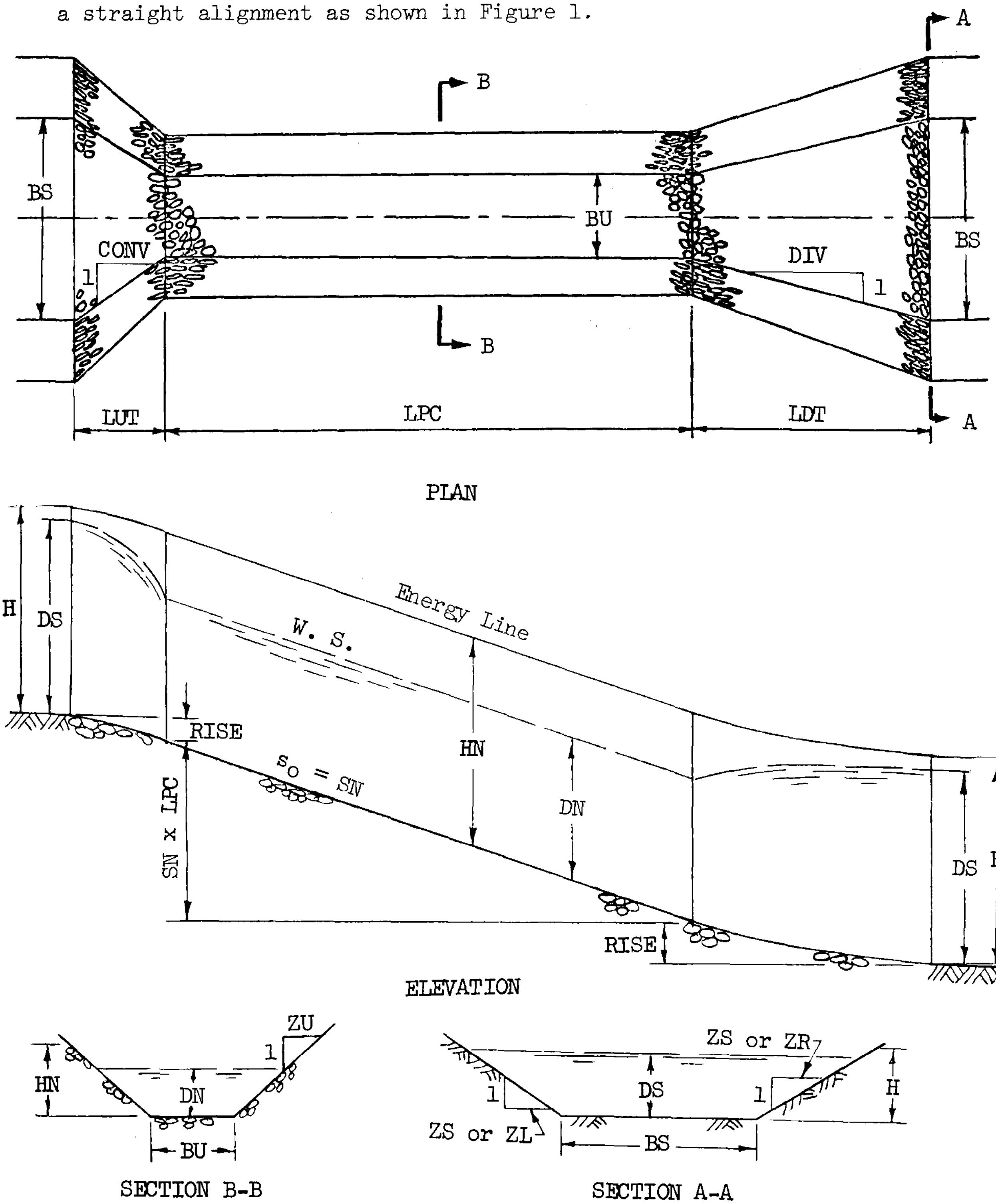


Figure 1. Riprap gradient control structure

Riprap Structure Concept

The following discussion on energy dissipation will assist in the understanding of the principles used in the development of the riprap structure concept and the reason for designing it to maintain a constant specific energy head.

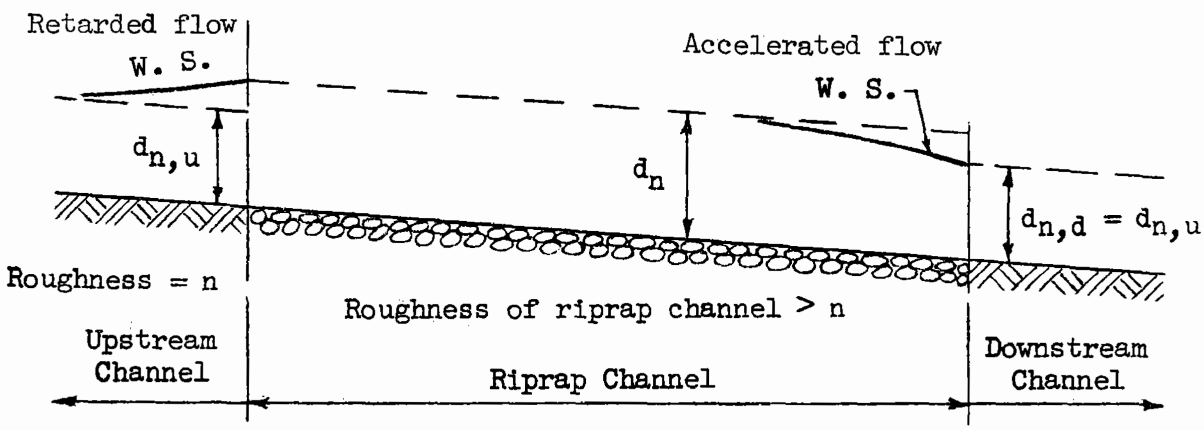
In a system of channels having mild slopes, i.e., flows are subcritical, the depth of flow for a given discharge is physically fixed by the downstream characteristics of the channel system and upstream characteristics have no effect on this depth. Since flows are subcritical, water surface profile computations are usually required for the channel downstream of the riprap prismatic channel or structure. These water surface profile computations evaluate the starting depth at the downstream end of the structure. For the purpose of stability analyses, the lowest probable starting depth corresponding to the discharge should always be used.

Consider a riprap channel and its adjoining upstream and downstream earth channels, all having the same dimensions and bottom slopes, but the riprap channel having a larger coefficient of roughness. Since the normal depth corresponding to a discharge, Q, in a prismatic channel is a function of the side slope, z, bottom slope, s_o, bottom width, b, and Manning's coefficient of roughness, n, the normal depth of the riprap channel will be greater than the normal depth of its adjoining channels. (See Figure 2a.) If the bottom slope of the riprap channel is increased sufficiently, the normal depth of the riprap channel, d_n, will be less than that of its adjoining channels. If the depth at the junction of the riprap channel and its adjoining channel downstream is equal to the normal depth of the downstream channel, $d_{n,d}$, then flow just upstream in the riprap channel is retarded flow. (See Figure 2b.) Thus the rate of friction loss is less than the bottom slope, and the velocity is increasing and the specific energy head is decreasing in the upstream direction. The maximum tractive stresses occur at the junction of the riprap channel and its adjoining upstream channel. The velocity may become so great that the upstream channel is unstable. In this situation the riprap roughness has not been used efficiently to dissipate energy.

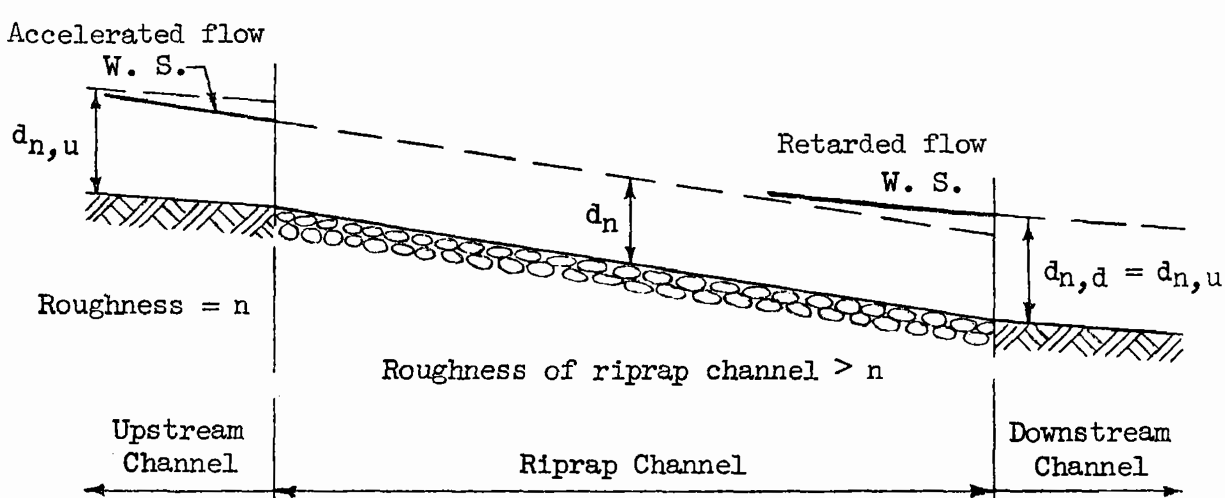
If the bottom slope of the riprap channel is adjusted such that the normal depth of the riprap channel equals the normal depth of the adjoining channels, the flow is uniform. Therefore, the rate of friction loss in the riprap channel is equal to its bottom slope and energy is dissipated uniformly. In this situation the riprap roughness is used more efficiently to dissipate energy. Furthermore, the specific energy head at the upstream end of the structure is equal to that at the downstream end. This is more compatible with a stable design of the upstream channel.

However, often the bottom slope of the riprap channel can be increased and the bottom width narrowed from a width, BS, to a width, BU, such that the specific energy head at normal depth in the riprap channel equals the specific energy head at the junction of the riprap channel and the downstream channel. Then the rate of friction loss in the riprap channel equals its bottom slope, s_n. Since the bottom slope is increased and the rate of friction loss equals the bottom slope, more energy dissipation is obtained in the same length of riprap channel. Thus, the riprap roughness is used more efficiently than in any of the previously considered riprap channels.

Also, since the bottom slope is increased and the bottom width is decreased, less riprap is required. Of course, when the riprap channel has been narrowed to the width BU < BS, transitions of sufficient length are required to convert potential energy to kinetic energy, and vice versa, with acceptable distribution of velocities. This reasoning leads directly to the riprap structure shown in Figure 1.



(a). Riprap channel and its adjoining channels have same bottom slope and bottom width



(b). Riprap channel has the same bottom width but steeper bottom slope than its adjoining channels

Figure 2. Development of riprap structure concept

Hydraulic Design of Structure

The design procedures for stability in this technical release have been confined to clear water flows. The conveyance of bed loads presents a much more complex set of considerations. In the general stability problem involving bed loads, the channel is designed for both clear water and bed load flows; each design fulfilling the capacity and stability requirements. Thus, such a design requires that the capacity of the channel be sufficient in the fully aggraded state. In addition, the design requires that the banks will not slough, erode, or silt laterally and the bed will not aggrade or degrade beyond the design limits. Design for only clear water flows implies that the greatest degraded condition has occurred and that a certain amount of sediment may be carried in suspension, but there will be no future deposition of sediment to cause aggradation on the bed or banks.

Design Discharge

For purposes of this technical release, design discharge means the largest discharge for which stability of the channel or structure is required. The design discharge is assumed to be wholly within the banks of the structure. The design discharge of the riprap structure is the same as the design discharge used in evaluating the stability of the channel at both ends of the structure.

Usually, structures that are stable for the design discharge will also be stable for all discharges less than the design discharge. However, if the structure tailwater decreases very rapidly with small decreases in discharge, theoretically discharges less than the design discharge may cause higher tractive stresses than the design discharge. In this case the lesser discharge would actually control the design. Thus where tailwater changes very rapidly with respect to discharge, designs should be obtained for the design discharge and several lesser discharges.

If a discharge occurs which is greater than the design discharge, the structure may not function properly. Therefore, it is important that the design discharge, Q, be selected sufficiently large to minimize the possibility of extensive damage during the design life of the channel and structure.

Specific Energy Head

When the bottom slope is subcritical, the normal depth is greater than critical depth. If the depth of flow is normal, then the rate of friction loss is equal to the bottom slope. This implies that all energy gained by virtue of the drop through the riprap structure is dissipated by friction losses. Normal or uniform flow may be characterized as flow at a constant specific energy head. Specific energy head is given by

$$H = d + \frac{v^2}{2g} = d + \frac{Q^2}{2ga^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Observe that a channel not flowing at critical depth has two depths corresponding to the same specific energy head; one depth is subcritical and the other is supercritical. All intervening depths have a smaller specific energy head. Therefore, if flow in the channel downstream of the structure is subcritical, supercritical flow cannot occur anywhere in the riprap structure if the structure maintains constant specific energy head and slopes are subcritical.

Manning's Roughness Coefficient

The predetermination that a riprap channel will flow at a constant specific energy head for a given discharge requires a careful evaluation of Manning's coefficient of roughness, n, for the channel and also the careful establishment of the tailwater elevation at the downstream end of the structure. The coefficient of roughness, n, for riprap has been experimentally evaluated as

$$n = C_n(D_{50})^{EXPN} \qquad (2)$$

where (from Report 108) $C_n = 0.0395$
$EXPN = 1/6$

Maximum Slope of Prismatic Channel

When the bottom slope of a channel is near the critical slope corresponding to a particular discharge, flow in the channel at this discharge is considered unstable, i.e., the depth of flow at a section is unpredictable because the depth fluctuates rapidly with any change in boundary condition. For this reason the prismatic channel bottom slope, s_n, is set equal to or less than 0.7 of the critical slope, s_c. The bottom slope, s_n, will be expressed as a fraction of the critical slope, i.e.,

$$s_n = CS(s_c) \qquad (3)$$

where $0 < CS \leq 0.7$

Prismatic Channel

The depth of flow in the prismatic channel of the riprap structure is set equal to the normal depth corresponding to the design discharge, Q. Therefore, the dissipation of hydraulic energy is at the same rate as the energy gain due to the gradient. The specific energy head, H, at every section of the riprap structure is set equal to the specific energy head of the downstream channel at the junction of the downstream transition and the downstream channel, Section A-A of Figure 1.

The following development shows that there is a unique prismatic channel bottom width which will meet the above requirement for a given set of values of Q, H, z, and CS. However, this theoretical procedure is not used directly in the computer program due to its obvious complexity. Instead, a procedure involving a series of iterations is used as outlined in the "Computer Program" section.

The discharge, Q, flowing at normal depth, d_n, in a channel of bottom width, b, and bottom slope, s_n, where $s_n = CS(s_c)$, is from Manning's formula

$$Q^2 = \left[\frac{1.486}{n}\right]^2 \frac{a_n^{10/3}}{p_n^{4/3}} CS(s_c) \qquad (4)$$

The discharge, Q, flowing at normal depth $d_n = d_c$, in a channel of bottom width, b, and bottom slope, s_c, is

$$Q^2 = \left[\frac{1.486}{n}\right]^2 \frac{a_c^{10/3}}{p_c^{4/3}} s_c \quad \ldots \quad (5)$$

Equating equations (4) and (5)

$$\frac{a_c^{10/3}}{p_c^{4/3}} = \frac{a_n^{10/3}}{p_n^{4/3}} \text{ CS} \quad \ldots \quad (6)$$

Let $x_c = \frac{d_c}{b}$, $x_n = \frac{d_n}{b}$, and z = the side slope of a trapezoidal section, and expand equation (6)

$$\frac{b^{20/3}\left[(1 + z\,x_c)x_c\right]^{10/3}}{b^{4/3}\left[1 + 2x_c\sqrt{z^2+1}\right]^{4/3}} = \frac{b^{20/3}\left[(1 + z\,x_n)x_n\right]^{10/3}}{b^{4/3}\left[1 + 2x_n\sqrt{z^2+1}\right]^{4/3}} \text{ CS}$$

or

$$\frac{\left[(1 + z\,x_c)x_c\right]^{10}}{(1 + 2x_c\sqrt{z^2+1})^4} = \frac{\left[(1 + z\,x_n)x_n\right]^{10}}{(1 + 2x_n\sqrt{z^2+1})^4} (\text{CS})^3 \quad \ldots \quad (7)$$

Equation (7) gives the relation of the critical depth, d_c, and normal depth, d_n, of a channel having a bottom slope, $s_o = s_n = \text{CS}(s_c)$. Observe that the relation is independent of Manning's n value. The functional relationship of equation (7) is:

$$x_n = f(x_c, z, \text{CS}) \quad \ldots \quad (7a)$$

The discharge, Q, corresponding to the critical depth, d_c, is

$$Q^2 = g\,\frac{a_c^3}{T_c} \quad \ldots \quad (8)$$

again let $x_c = \frac{d_c}{b}$ and expand equation (8)

$$\frac{Q^2}{b^5} = \frac{g\left[(1 + z\,x_c)x_c\right]^3}{(1 + 2z\,x_c)} \quad \ldots \quad (9)$$

or

$$x_c = f_1\left[\frac{Q}{b^{5/2}}, z\right] \quad \ldots \quad (9a)$$

From equations (7a) and (9a) and for a given value of CS

$$x_n = f_2\left[\frac{Q}{b^{5/2}}, z\right] \quad \ldots \quad (10)$$

The specific energy head, H, in the riprap structure is

$$H = d_n + \frac{Q^2}{2g}\frac{1}{a_n^2} \quad \ldots \quad (11)$$

dividing by b, expanding, and letting $x_n = \frac{d_n}{b}$

$$\frac{H}{b} = \frac{d_n}{b} + \frac{Q^2}{2g\, a_n^{\,2}\, b} = x_n + \frac{Q^2}{b^5}\left[\frac{1}{2g\left[(1 + z\, x_n)\, x_n\right]^2}\right] \quad \ldots \quad (12)$$

or

$$\frac{H}{b} = f_3\left[\frac{Q}{b^{5/2}},\; z,\; x_n\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (12a)$$

From equations (10) and (12a) and for a given value of CS

$$\frac{H}{b} = f_4\left[\frac{Q}{b^{5/2}},\; z\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (13)$$

Rearranging equation (12)

$$\frac{Q^2}{b^5} = \left[2g\left(\frac{H}{b} - x_n\right)\right]\left[(1 + z\, x_n)x_n\right]^2$$

Taking the square root and multiplying by $\left[\frac{b}{H}\right]^{5/2}$

$$\frac{b^{5/2}}{H^{5/2}}\,\frac{Q}{b^{5/2}} = \frac{Q}{H^{5/2}} = \left[2g\,\left(\frac{H}{b} - x_n\right)\right]^{1/2}\left[(1 + z\, x_n)x_n\right]\left[\frac{b}{H}\right]^{5/2}$$

$$\frac{H}{b} = f_5\left[\frac{Q}{H^{5/2}},\; z,\; x_n\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (14)$$

Repeating equations (10) and (13)

$$x_n = f_2\left[\frac{Q}{b^{5/2}},\; z\right]$$

$$\frac{H}{b} = f_4\left[\frac{Q}{b^{5/2}},\; z\right]$$

Thus, for a given value of CS

$$x_n = f_6\left(\frac{H}{b},\; z\right) \quad \ldots\ldots\ldots\ldots\ldots \quad (15)$$

Combining equations (14) and (15)

$$\therefore\; \frac{H}{b} = f_7\left[\frac{Q}{H^{5/2}},\; z\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (16)$$

Thus, for a given design discharge, Q, flowing at normal depth, d_n, and for given values of H, z, and CS, there exists one unique bottom width, b. However, it should be noted that a solution is not always possible.

The relation given in equation (16) is independent of the value of the parameter D_{50}. However, the critical slope, s_c, depends on the value of n, and n is a function of D_{50} since from equation (2), $n = C_n(D_{50})^{1/6}$. Therefore, the slope of the prismatic channel, s_n, depends on the D_{50} size of the riprap.

Thus, from equation (5)

$$s_c = \frac{n^2\, Q^2}{1.486^2}\;\frac{p_c^{\,4/3}}{a_c^{\,10/3}} = \frac{C_n^{\,2}\, D_{50}^{\,1/3}\, Q^2}{1.486^2}\;\frac{p_c^{\,4/3}}{a_c^{\,10/3}} \quad . \; . \; . \; . \; . \qquad (17)$$

or

$$\frac{s_c}{D_{50}^{\,1/3}} = \left[\frac{C_n\, Q}{1.486}\right]^2 \frac{p_c^{\,4/3}}{a_c^{\,10/3}} = \left[\frac{C_n\, Q}{1.486}\right]^2 \frac{\left[b(1 + 2x_c\sqrt{z^2+1})\right]^{4/3}}{\left[b^2\, x_c(1 + z\, x_c)\right]^{10/3}}$$

or

$$\frac{s_c}{D_{50}^{\,1/3}} = \left[\frac{C_n}{1.486}\right]^2 \frac{Q^2}{b^5}\left[\frac{(1 + 2x_c\sqrt{z^2+1})^{4/3}}{b^{1/3}\left[x_c(1 + z\, x_c)\right]^{10/3}}\right] \quad . \; . \; . \qquad (18)$$

and from equation (3), $s_n = CS(s_c)$

Transitions

The function of a transition is to convert potential energy to kinetic energy, or vice versa, in such a manner that an acceptable velocity distribution is provided. Generally, transitions are designed to avoid excessive energy losses in the flows they convey. This function is contrary to the goal of the designer of transitions for these gradient control structures. However, the design for either function leads to the same basic proportioning of the transition.

Converging inlet transitions located at the upstream end of the riprap structures are designed with a rate of convergence of the bottom width, CONV. The length of the upstream transition, LUT, is equal to $\text{CONV}\left[\frac{BS - BU}{2}\right]$. The inlet transition conveying the design discharge, Q, at subcritical flow, converts potential energy to kinetic energy. The velocity increases and the depth decreases in the direction of flow. See Figure 1.

Diverging outlet transitions located at the downstream end of the riprap structures are designed with a rate of divergence of the bottom width, DIV. The length of the downstream transition, LDT, is equal to $\text{DIV}\left[\frac{BS - BU}{2}\right]$. Flows in diverging transitions are expanding. If the rate of divergence is too rapid, the expanding flows tend to separate from the boundary and an uneven velocity distribution may occur. Therefore, a long transition is required to ensure an acceptable velocity distribution. The outlet transition converts kinetic energy to potential energy, and the velocity decreases and depth increases in the direction of flow.

The transitions associated with the riprap structure are designed to convey the design discharge, Q, throughout the transitions at a constant specific energy head, H. To maintain a constant H when the bottom width is changing requires that the bottom slope of the transition be variable, changing from the slope of the riprap prismatic channel to flatter slopes at the upstream and downstream ends of the structure. The instantaneous bottom slope at any section of the transition is equal to the rate of friction head loss at that section when the design discharge, Q, is flowing at normal depth, d_n, and at the design specific energy head, H.

The bottom width of the transition, b_j, varies linearly from BS to BU through the length of transition, LT. The side slope, z, also varies linearly from ZS to ZU through the length, LT. Thus, at a particular section, j, of the transition

$$b_j = BU + J(BS - BU) \quad \text{and}$$

$$z = ZU + J(ZS - ZU)$$

where

$$J = \frac{\text{Distance in the transition from section j to section of width BU}}{LT}$$

Thus at a section j the constant specific energy head, H, is

$$H = d + \frac{Q^2}{2g\left[(b_j + zd)d\right]^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

The rate of energy loss, s, at section j of the transition having a bottom slope, s_o, and conveying the design discharge, Q, at normal depth, d_n, is

$$s = s_o\left[\frac{Q}{Q_{n,d}}\right]^2 = \frac{Q^2\, n^2\, p_n^{4/3}}{(1.486)^2\, a_n^{10/3}} \quad \ldots\ldots\ldots\ldots\ldots \quad (20)$$

where

$$p_n = b_j + 2d_n\sqrt{z^2 + 1}$$

$$a_n = (b_j + zd_n)d_n$$

The bottom slope of the transition at section j is equal to the energy slope, s.

Conversion losses in the transitions are not considered in the design of the riprap structure since a more conservative design of the structure is obtained by ignoring these losses. If the conversion losses were considered, the depth of flow in the structure would be increased slightly, the velocity decreased, and the tractive stress decreased. However, the conversion losses may be significant in the determination of an upper limit for the water surface profile upstream of the riprap structure, particularly where structures are used in series and some accumulation of conversion losses may occur.

The approximate conversion losses are given in the computer output following the riprap structure design. The equations used to determine the conversion losses are taken from Henderson[2]

$$\text{Conversion head loss in diverging transition} = \frac{0.3(VN-VS)^2}{2g}$$

$$\text{Conversion head loss in converging transition} = \frac{C(VN)^2}{2g}$$

$$\text{When } \frac{DN}{BU} \le 1.0 \;; \quad C = 0.04$$

$$\frac{DN}{BU} \ge 1.3 \;; \quad C = 0.11$$

In the computer program when $1.0 < \frac{DN}{BU} < 1.3$, the coefficient, C, varies linearly from 0.04 to 0.11.

[2] F. M. Henderson. "Open Channel Flow" (The MacMillan Company, New York; Collier-MacMillan, Canada, LTD., Toronto, Ontario, 1966), p. 237-238.

Design of Riprap

Riprap as used in this technical release consists of loose rocks or granulars of rock having a unit weight of approximately 165 lbs/ft^3. The individual rocks or granulars have no cohesive property nor are they cemented. The experimental results in Report 108 show the D_{50} size of the riprap varying approximately within the interval:

$$3.3 \times 10^{-4} \text{ ft} (\approx 0.1 \text{ mm}) \leq D_{50} \leq 1.0 \text{ ft } (\approx 305 \text{ mm})$$

where

$D_{50} \equiv$ Size of rock in riprap of which 50 percent by weight is finer, ft.

Thus, channels constructed in granular noncohesive materials of sufficient size, such as loose sands and gravels, may be designed using the same procedures used for riprap channels.

The riprap is designed to prevent significant movement of the rock when the structure is conveying the design discharge, Q. The stability design is accomplished by providing

1. riprap of sufficient size that no significant movement of the individual rocks or particles occurs due to the tractive stresses caused by the flow and

2. riprap lining of sufficient thickness or the combination of riprap lining and filter layer to prevent leaching.

The following discussion defines the critical and allowable tractive stresses as related to riprap D_{50} size and describes how to obtain the values of the actual maximum tractive stress on the sides and bottom of a prismatic channel. Then, the criteria for determining the minimum acceptable riprap size is given along with other riprap requirements.

Critical Tractive Stress

The critical tractive stress is that tractive stress which initiates movement of the riprap. For a given riprap size, the tractive stress required to initiate movement is less for riprap placed on the side slopes of a trapezoidal channel than for riprap placed on the bottom of the channel. The critical tractive stress for riprap on the bottom of the channel, τ_{bc}, as obtained from experimentation is approximately a linear function of the riprap size, D_{50}.

$$\tau_{bc} = C_{50} D_{50} \quad \ldots \quad (21)$$

where $C_{50} = 4.0$ (from Report 108)

Riprap placed on the side slopes of a trapezoidal channel is subjected to the gravitational force, which tends to pull the riprap down the side slope, in addition to the tractive stress caused by the flow. The critical tractive stress for riprap placed on the side slope of the trapezoidal channel, τ_{sc}, being somewhat less than τ_{bc}, is set equal to K times τ_{bc}. The coefficient, K, depends chiefly on the angle of repose, θ, of the riprap and the side slope, z, on which the riprap is placed. The angle of repose depends on the size, angularity, and shape of the riprap. Approximate values of the angle of repose are given by Figure 16 in Report 108. The relation of K, θ, and z is often taken as

$$K = \frac{\tau_{sc}}{\tau_{bc}} = \sqrt{1 - \frac{\sin^2 (\cot^{-1} z)}{\sin^2 \theta}} \quad \ldots \ldots \ldots \ldots \ldots (22)$$

The critical tractive stress for riprap placed on a side slope becomes

$$\tau_{sc} = K\ \tau_{bc} = K\ C_{50}\ D_{50} \quad \ldots \ldots \ldots \ldots \ldots (23)$$

Allowable Tractive Stress

As with many engineering calculations, a factor of safety, FS, is applied to determine the allowable tractive stress. The allowable tractive stress is obtained by dividing the critical tractive stress by the factor of safety. Thus, the allowable tractive stress for the channel bottom, τ_{ba}, and for the side slopes, τ_{sa}, becomes

$$\tau_{ba} = \frac{C_{50}\ D_{50}}{FS} \quad \ldots \ldots \ldots \ldots \ldots (24)$$

$$\tau_{sa} = \frac{K\ C_{50}\ D_{50}}{FS} \quad \ldots \ldots \ldots \ldots \ldots (25)$$

Average Tractive Stress

The average tractive stress, τ_{av}, may be analytically ascertained by the assumption that all frictional losses are caused by frictional forces on the boundary of the riprap lining. This frictional force, F_f, acting on a moving body of water in a direction opposite to that of the flow is shown in Figure 3.

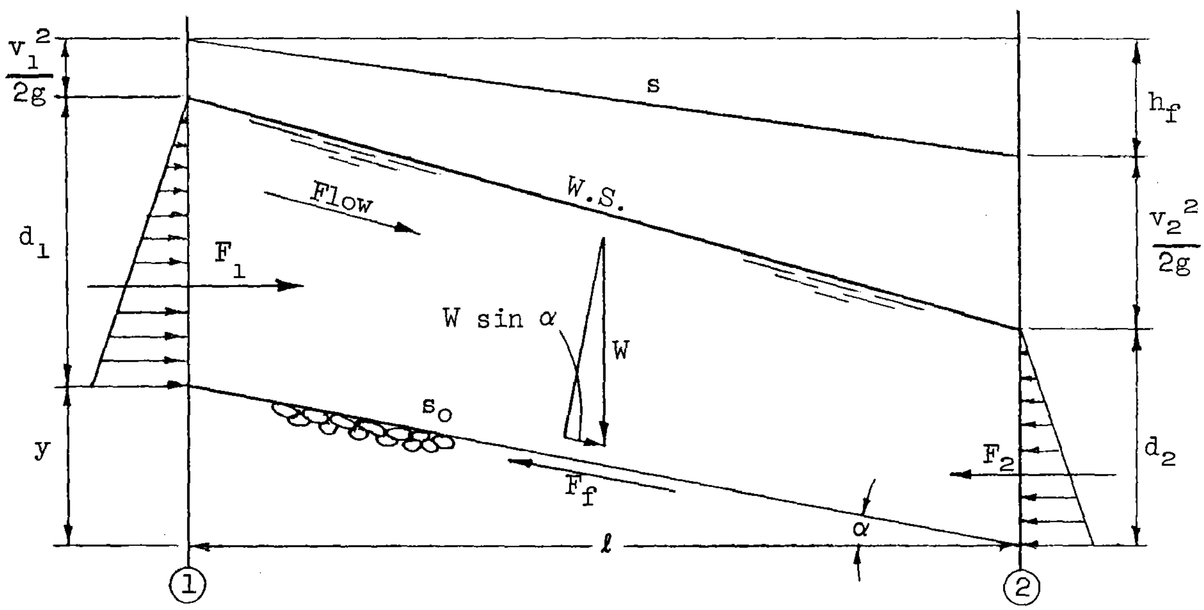


Figure 3. Forces acting on a moving body of water

Assumptions; $\sin \alpha = \tan \alpha = s_o$ and $\cos \alpha = 1$

$$F_1 = \frac{\gamma\, b_a\, d_1^2}{2}$$

$$F_2 = \frac{\gamma\, b_a\, d_2^2}{2}$$

average velocity, $v_a = \frac{v_1 + v_2}{2}$

average flow area, $a_a = b_a\left(\frac{d_1 + d_2}{2}\right)$

where

v_1 and v_2 ≡ average velocity at Sections 1 and 2 respectively
b_a ≡ average width of the channel

From Newton's second law of motion

$$F = M\,\frac{dv}{dt}$$

Where from Figure 3;

$M = \frac{\gamma\, Qdt}{g}$ ≡ mass of body of water between Sections 1 and 2

dt ≡ time interval for flow to move from Section 1 to Section 2

dv ≡ the change in velocity of flow between Section 1 and Section 2

$F = F_1 - F_2 + \cos \alpha(W \sin \alpha - F_f)$ ≡ Summation of all horizontal forces acting on the body of moving water

$$F = F_1 - F_2 + W\, s_o - F_f = \frac{\gamma\, Qdt}{g}\left(\frac{v_2 - v_1}{dt}\right)$$

$$F_f = F_1 - F_2 + W\, s_o + \frac{\gamma Q(v_1 - v_2)}{g} \quad \ldots\ldots\ldots\ldots \quad (26)$$

The energy loss in ft-lb per pound of water between sections 1 and 2 is equal to $F_f\ell$ divided by the weight of water, W,

or

$$\frac{F_f\ell}{W} = \frac{F_f\, v_a\, dt}{\gamma\, Q\, dt} = \frac{F_f}{\gamma\, a_a}$$

Substitute the values of F_1, F_2, and $W\, s_o$ into Equation (26) and divide by $\gamma\, a_a$

$$\frac{F_f}{\gamma\, a_a} = \frac{\gamma\, b_a}{2\gamma\, a_a}\,(d_1^2 - d_2^2) + \frac{\gamma\, Q\, dt}{\gamma\, a_a}\,\frac{y}{\ell} + \frac{\gamma\, Q}{\gamma\, a_a\, g}\,(v_1 - v_2)$$

$$\frac{F_f}{\gamma\, a_a} = b_a\,\frac{(d_1 + d_2)}{2}\,\frac{(d_1 - d_2)}{a_a} + v_a\, dt\,\frac{y}{\ell} + v_a\left(\frac{v_1 - v_2}{g}\right)$$

$$\frac{F_f}{\gamma\, a_a} = a_a\,\frac{(d_1 - d_2)}{a_a} + \frac{\ell y}{\ell} + \frac{(v_1 + v_2)}{2}\,\frac{(v_1 - v_2)}{g}$$

$$\frac{F_f}{\gamma\, a_a} = d_1 - d_2 + y + \frac{v_1^2 - v_2^2}{2g} \quad \ldots\ldots\ldots\ldots \quad (27)$$

From Bernoulli's equation of conservation of energy, the total energy at Section 1 is equal to the total energy at Section 2 plus the energy loss between Sections 1 and 2; refer to Figure 3.

$$y + d_1 + \frac{v_1^2}{2g} = d_2 + \frac{v_2^2}{2g} + h_f$$

$$h_f = d_1 - d_2 + y + \frac{v_1^2 - v_2^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (28)$$

$\therefore\ h_f = \dfrac{F_f}{\gamma\, a_a} \equiv$ total energy loss between Sections 1 and 2 in ft-lb per pound of water

or

$$F_f = \gamma\, a_a\, h_f$$

The average tractive stress, τ_{av}, in pounds per unit area, on the boundary of the riprap lining is equal to F_f divided by $p\ell$

$$\tau_{av} = \frac{F_f}{p\ell} = \gamma\, \frac{a}{p}\, \frac{h_f}{\ell} = \gamma\, rs \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (29)$$

where $\gamma \equiv$ Unit weight of water = 62.4 lb/ft^3

$r = \dfrac{a}{p} \equiv$ Hydraulic radius, ft

$a \equiv$ Flow area, ft^2

$p \equiv$ Wetted perimeter of riprap lining, ft

$s = s_o\left(\dfrac{Q}{Q_{n,d}}\right)^2 \equiv$ Rate of friction loss, ft/ft

Distribution of Tractive Stress

Tractive stresses are not uniformly distributed along the boundary of the riprap lining, see Figure 4. The maximum tractive stress depends on

1. the ratio of the bottom width, b, to the depth of flow, d, and
2. the side slope of the channel, z.

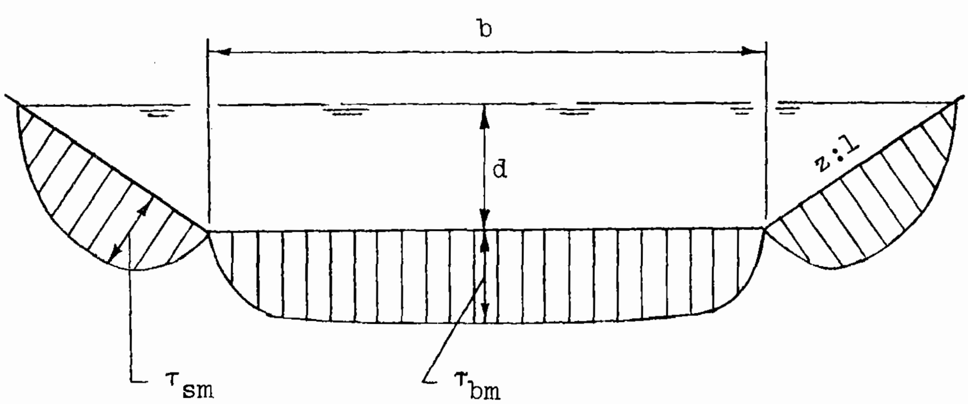


Figure 4. Distribution of tractive stress along the wetted perimeter of a riprap lining

Usually the maximum tractive stress is on the bottom of the riprap section. For small values of $\frac{b}{d}$, the maximum tractive stress is on the side slopes of the riprap section, see Figures 5 and 6. These figures, obtained from Report 108, give the values of $C_{\tau s} = \frac{\tau_{sm}}{\tau_{av}}$ and $C_{\tau b} = \frac{\tau_{bm}}{\tau_{av}}$, respectively. τ_{sm} is the maximum tractive stress along the riprap lining on the side slopes of the channel and τ_{bm} is the maximum tractive stress along the riprap lining on the bottom of the trapezoidal section.

Minimum Acceptable Riprap Size

The minimum acceptable riprap size is determined from one of the following two criteria, whichever controls:

1. the maximum tractive stress along the bottom, τ_{bm}, must be equal to or less than the allowable tractive stress for the riprap on the bottom

$$\tau_{bm} \leq \tau_{ba}$$

where

$$\tau_{bm} = C_{\tau b}\ \gamma\ r\ s$$

$$\tau_{ba} = \frac{C_{50}\ D_{50}}{FS}$$

2. the maximum tractive stress along the sides, τ_{sm}, must be equal to or less than the allowable tractive stress for the riprap on the sides.

$$\tau_{sm} \leq \tau_{sa}$$

where

$$\tau_{sm} = C_{\tau s}\ \gamma\ r\ s$$

$$\tau_{sa} = \frac{K\ C_{50}\ D_{50}}{FS}$$

Thus, to prevent movement of the individual rocks or particles by the tractive stress caused by the flow, the above two conditions must be satisfied at every section in the riprap structure.

Riprap Gradation

The riprap gradation should yield a smooth size distribution curve and the riprap should not be skip graded. The recommended Gradation Index evaluated from the distribution curves for the materials used in the channel stability experiments of Report 108 is

$$\text{Gradation Index} = \left[\frac{D_{85}}{D_{50}} + \frac{D_{50}}{D_{15}}\right] \leq 5.5$$

The riprap gradation affects the required thickness of riprap lining. For well graded riprap, the interstices between larger rocks are filled with smaller rocks; thus the leaching potential is reduced and the required riprap lining thickness is smaller than that for a more uniformly graded riprap. Therefore, as the gradation index increases, the riprap lining thickness may be decreased.

Filter

Leaching is the process by which the finer base materials beneath the riprap are picked up and carried away by the turbulence that penetrates the interstices of the riprap. Leaching is reduced to a negligible rate by using a properly designed filter under the riprap or by making the riprap layer thick enough and with fine enough interstices to keep erosive currents away from underlying soil.

Report 108 recommends the use of a filter layer if the following criteria are not met:

$$\frac{D_{15}\ \text{Riprap}}{D_{85}\ \text{Base}} < 5 < \frac{D_{15}\ \text{Riprap}}{D_{15}\ \text{Base}} < 40$$

$$\frac{D_{50}\ \text{Riprap}}{D_{50}\ \text{Base}} < 40$$

where D_{15}, D_{50}, and D_{85} are the sizes of riprap and base material of which 15, 50, and 85 percent are finer by weight.

Thickness of Riprap Lining

The required thickness of the riprap lining is based largely on experience. Construction techniques, discharge, size of channel, sizes and gradation of riprap, etc., should be taken into consideration when determining the thickness of riprap lining. The following three criteria for thickness of riprap lining have been suggested:

1. a thickness of three times the D_{50} size if a filter layer is not used
2. a thickness of one and a half to two times the D_{50} size if a filter layer is used
3. a thickness at least one and a half times the maximum particle size if a filter layer is used.

Riprap Quantity in Prismatic Channel

The wetted perimeter, p_n, and bottom slope, s_n, associated with the design of a riprap structure affect the quantity of riprap. For a given design and amount of gradient control required in the prismatic channel, the least amount of riprap is obtained when the value of $\frac{p_n}{s_n}$ is minimum. A side slope, ZU, in the range of 2, 2.5, or 3 usually yields a minimum value of $\frac{p_n}{s_n}$.

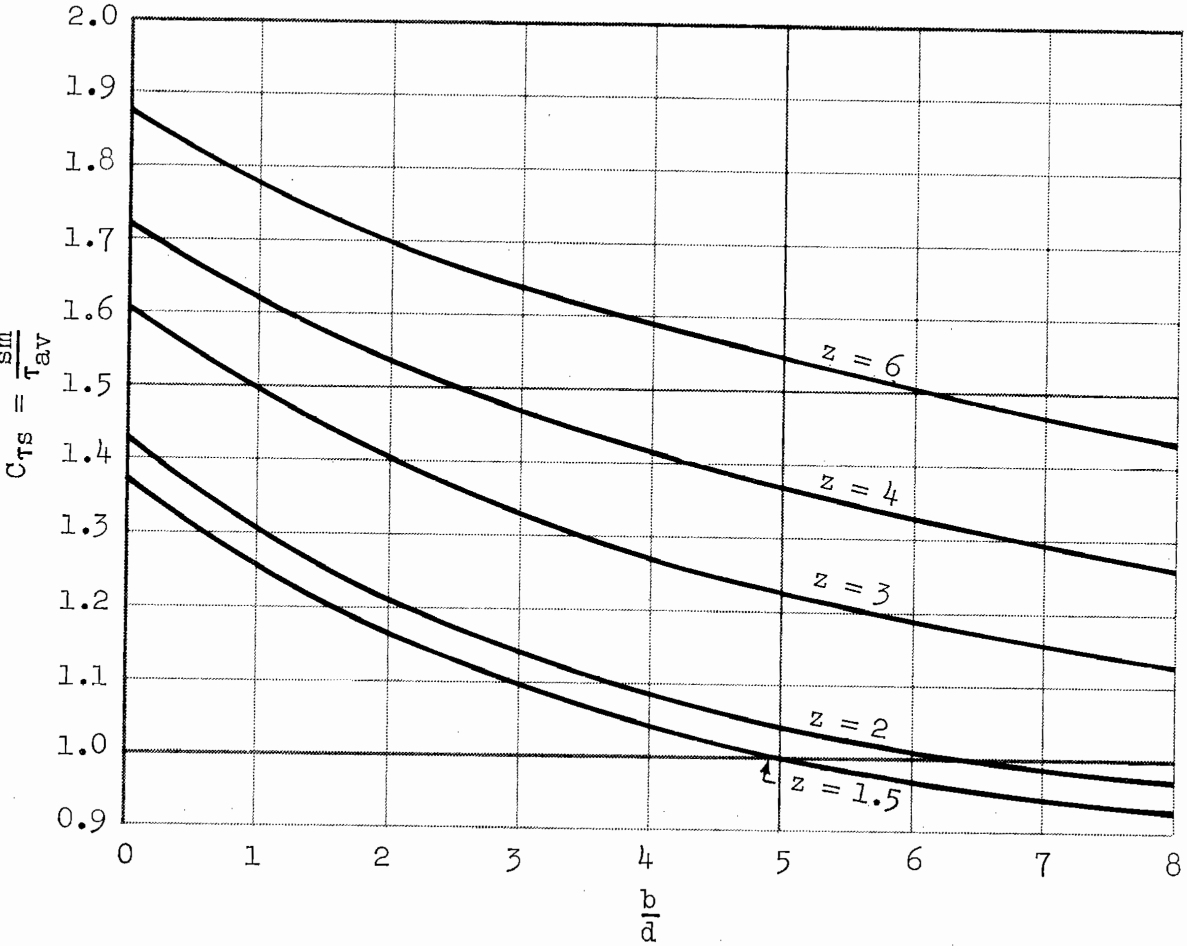


Figure 5. Maximum tractive stress on sides of trapezoidal channels

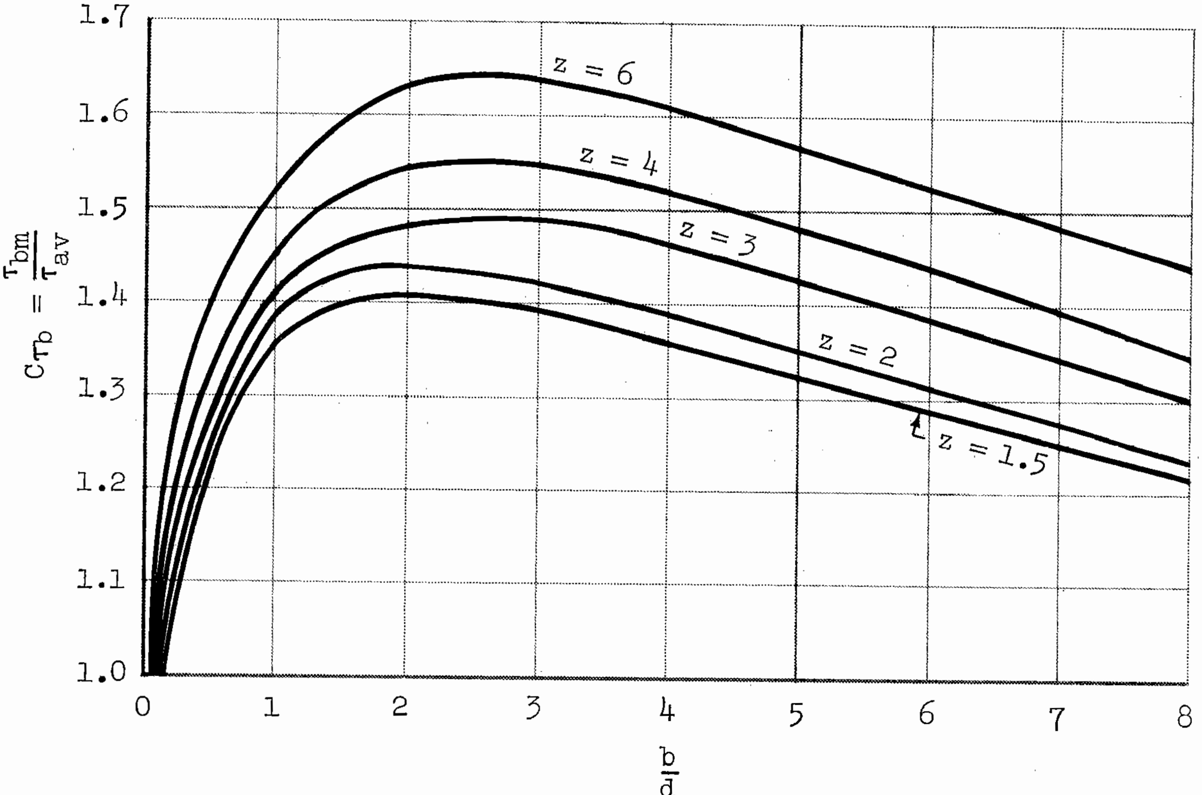


Figure 6. Maximum tractive stress on bottom of trapezoidal channels

Summary of Design Criteria

The following basic criteria govern the design of the riprap structure:

1. The specific energy head, H, at every section of the riprap structure is set equal to the specific energy head at the junction of the downstream transition and the downstream channel, Section A-A of Figure 1. Specific energy head is given by

$$H = d + \frac{v^2}{2g} = d + \frac{Q^2}{2ga^2}$$

2. The prismatic channel bottom slope, s_n, is set equal to or less than 0.7 of the critical slope, s_c. The bottom slope, s_n, is expressed as a fraction of the critical slope, i.e.,

$$s_n = CS(s_c)$$

$$\text{where} \quad 0 < CS \leq 0.7$$

3. Manning's coefficient of roughness, n, is a function of the D_{50} size of the riprap and has been evaluated to be

$$n = 0.0395\,(D_{50})^{1/6}$$

4. The critical tractive stress is a linear function of the D_{50} size of the riprap, i.e.,

$$\tau_{bc} = 4.0\,D_{50}$$

$$\tau_{sc} = K(4.0\,D_{50})$$

5. The riprap size and structure dimensions are selected so that for the design discharge the maximum tractive stress on the riprap does not exceed the allowable tractive stress. Either side or bottom tractive stress may control.

For a given design discharge, Q, specific energy head, H, and side slope, z, the variables that must be adjusted to meet these conditions are bottom width, b; bottom slope, s_o; and riprap size, D_{50}.

The length of the prismatic channel, LPC, is equal to the vertical drop of the prismatic channel divided by the bottom slope, s_n. The vertical drop of the prismatic channel depends on the amount of gradient control required.

Computer Program

A computer program is available which determines dimensions and parameters associated with the design of a riprap gradient control structure. The structure is designed to flow at a constant specific energy head when conveying the design discharge, Q. The design is made for either the maximum D50 riprap size or for the maximum CS value, whichever controls.

The parameters Q, ZU, and H (or the equivalent of H, in terms of two of the parameters BS, DS and VS) are always input to the program. The solution for each design is highly implicit. Two basically different design approaches are used in the program. The applicable approach depends on whether or not D50 is specified by the user. These two approaches in simplified form are shown in the flow chart of Figure 7.

Default values are used for certain parameters if their values are not specified by the user. These parameters are called default parameters.

Modes

The computer program operates in one of four modes numbered 1 through 4. A mode must be specified for each design run. A computer job may contain one or more design runs consisting of the same or different modes.

Mode 1 obtains only the design of a riprap prismatic channel. Modes 2, 3, and 4 obtain the design of the prismatic channel and both transitions of the riprap structure.

Mode 1 permits the specification of the default parameter, D50.

Mode 2 permits the specification of any or all of the three default parameters D50, CONV, and DIV. Mode 2 requires that two and only two of the four parameters H, BS, DS, and VS be specified; otherwise, the computer prints an error code and the computations for this design run cease.

Mode 3 is the same as mode 2 except for an additional line of input which permits the user to specify values for any or all of the default parameters CS, C50, FS, THETA, CN, and EXPN.

Mode 4 is the same as mode 3 except for the parameter, ZS; instead of ZS mode 4 requires the specification of ZL and ZR for different side slopes at the ends of the riprap structure. Also, in mode 4 the parameters BS and DS must be specified.

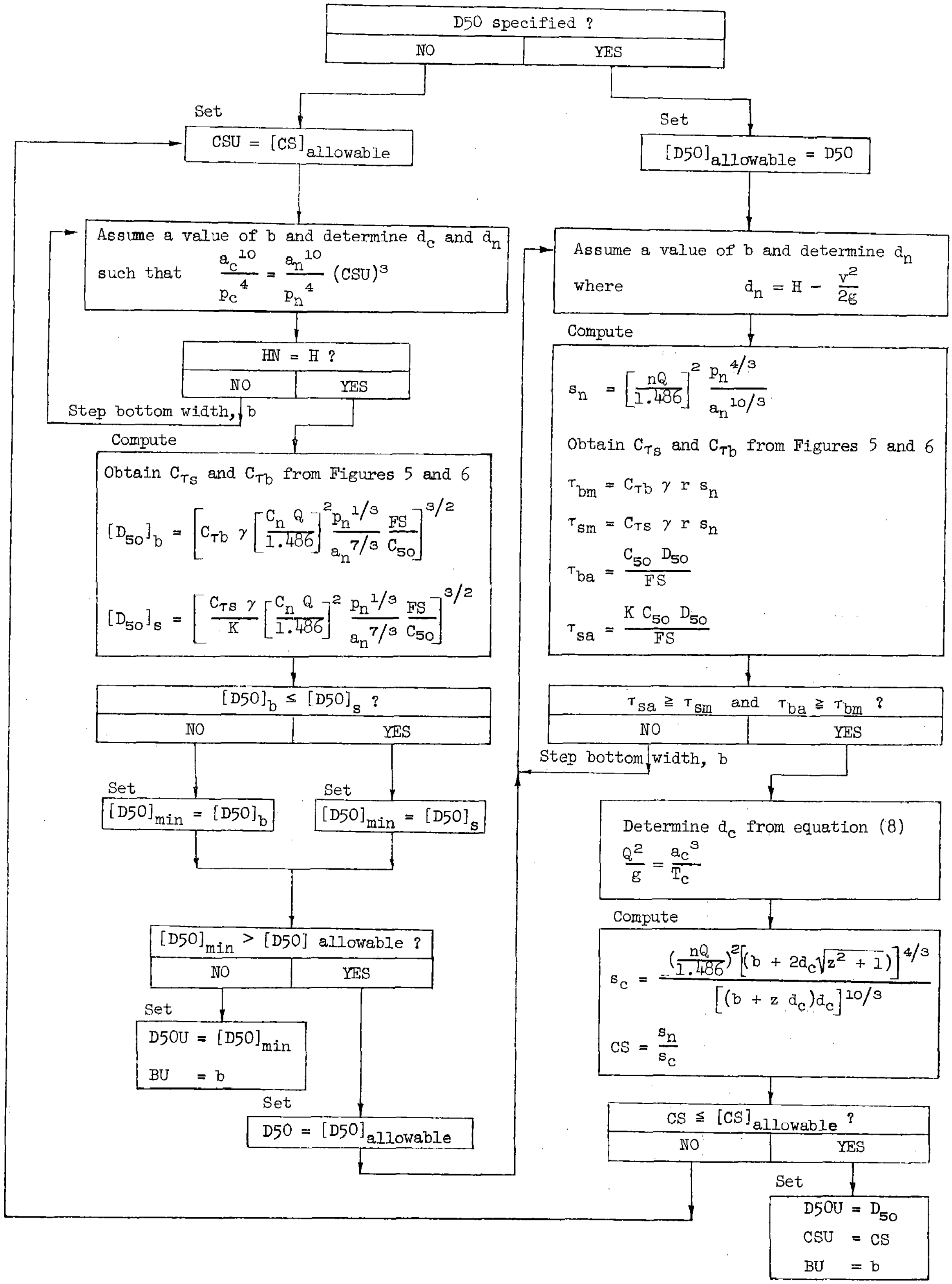


Figure 7. Flow chart of procedure used in computer program to determine the bottom width

Summary of Input Data

XX ≡ Required parameters

XX (boxed) ≡ Default parameters, default values used unless values are specified by the user

XX (dotted box) ≡ Two and only two of the four parameters, H, BS, DS, and VS are required

Mode	Required Lines	Order of Parameters							
1	1st line	–	1.0	Q	ZU	D50	H	–	–
2	1st line	–	2.0	Q	ZU	D50	H	–	–
	2nd line	–	ZS	–	BS	DS	VS	CONV	DIV
3	1st line	–	3.0	Q	ZU	D50	H	–	–
	2nd line	–	ZS	–	BS	DS	VS	CONV	DIV
	3rd line	–	CS	C50	FS	THETA	CN	–	EXPN
4	1st line	–	4.0	Q	ZU	D50	–	–	–
	2nd line	–	ZL	ZR	BS	DS	–	CONV	DIV
	3rd line	–	CS	C50	FS	THETA	CN	–	EXPN

Input Data

The line arrangement of input data and their locations for the four modes is given in the "Summary of Input Data" on the preceding page.

Required data common to all modes. Each computer job requires two lines of information. Each line consists of 80 or less alphanumeric characters. This information must be placed ahead of the other input data and is generally for identifying and documenting the designs. Other required data common to all modes are:

1. Mode number (1.0, 2.0, 3.0, or 4.0)
2. Q, design discharge to be conveyed within the prismatic channel of the riprap structure
3. ZU, side slopes of the prismatic channel of the riprap structure.

Other required data.

1. Mode 1 requires the specific energy head, H, corresponding to the design discharge.
2. Modes 2 and 3
   a. Two, and only two, of the parameters H, BS, DS and VS are required. The other two parameters are ascertained by the computer.

      BS ≡ Bottom width at the ends of riprap structure, ft

      DS ≡ Depth of flow at design discharge at the ends of riprap structure, ft

      VS ≡ Velocity at design discharge at the ends of riprap structure, ft/sec

   b. ZS, the side slope at the ends of riprap structure is required
3. Mode 4 requires ZL, ZR, BS, and DS. The specific energy head, H, and the velocity, VS, are defined by the specified BS and DS.

   ZL ≡ Side slope of the left bank at the ends of riprap structure, see SECTION A-A, Figure 1, ft/ft

   ZR ≡ Side slope of the right bank (looking downstream) at the ends of riprap structure, ft/ft

Default Parameters

All other parameter values required for the design are obtained by default unless they are specified. The specified value of each parameter must be greater than zero. Default parameters D50, CONV, and DIV may be specified in modes 2, 3, and 4. The remaining default parameters may be specified only in modes 3 and 4. A value of 0.0 or a blank for a default parameter is interpreted to mean the default value is to be used.

The default parameters D50 and CS have default values equal to their recommended maximum allowable values. These are:

D50 = 1.0 ft ⎤ Default values and recommended maximum
CS = 0.7 ⎦ allowable values

where

D50 ≡ Size of rock in riprap of which 50 percent by weight is finer, ft (D50 > 1.0 ft may be specified)

CS ≡ Ratio of normal slope, SN, to critical slope, SC

The default parameters CONV and DIV have default values equal to their recommended minimum allowable values. These are:

CONV = 2.0 ⎤ Default values and recommended minimum
DIV = 4.0 ⎦ allowable values

where

CONV ≡ Rate of convergence of the bottom width of the upstream transition, see Figure 1, ft/ft

DIV ≡ Rate of divergence of the bottom width of the downstream transition, ft/ft

The values of any of the following default parameters may be specified. The default values of these default parameters are:

FS = 1.25

C50 = 4.0

THETA = 35°

CN = 0.0395

EXPN = 0.1667

where

FS ≡ Factor of safety

C50 ≡ Coefficient used in the equation, $\tau_{bc} = C_{50} D_{50}$

THETA ≡ Angle of repose of the riprap, degrees

CN ≡ Coefficient used in the equation for computing Manning's roughness coefficient, $n = C_n \left[D_{50}\right]^{EXPN}$

EXPN ≡ Value of the exponent in the equation for computing Manning's roughness coefficient, n.

Limitations

When the input data are not consistent or have exceeded the limitations set in the program, a message will be printed out indicating the reason computations cannot be continued and what the next course of action will be. For example:

"FOR CS = 0.7000 THE COMPUTED VALUE OF D50 = 1.182 FT IS GREATER THAN THE SPECIFIED OR ALLOWABLE D50. SOLUTION FOR CS WILL BE MADE USING SPECIFIED OR ALLOWABLE D50 OF 1.000 FT."

For details of maximum and minimum allowable values and limitations, refer to the discussions under "Default Parameters" and the error codes under "Messages."

Output Data

The alphanumeric information in the first two lines of input are printed by each design run. The printed alphanumeric information is followed by the data used for the design run.

The output data for the dimensions and parameters of the structure are given in the following order:

1. Transition at the downstream end
2. Prismatic channel
3. Transition at the upstream end

The output for values of KPS and FRIC SLOPE are given in an E format code containing an exponent. The exponent is the power of 10 by which the output value is multiplied to obtain its true value. For example:

$$3.72E-03 = 3.72 \times 10^{-3} = 0.00372$$

The headings used for the output for the transitions are:

LENGTH FT − Length from the downstream end of the transition to any section j of the transition, ft

RISE FT ≡ The vertical distance from the bottom of the channel, at the downstream end of the transition, to the bottom of the channel at any section j in the transition, ft

WIDTH FT ≡ The bottom width at any section j in the transition, ft

Z ≡ Modes 2 and 3 only; the side slope at any section j in the transition, ft/ft

ZLT ≡ Mode 4 only; the left side slope at any section j in the transition, ft/ft

ZRT ≡ Mode 4 only; the right side slope at any section j in the transition, ft/ft

DEPTH FT ≡ The depth at any section j in the transition, ft

TOP WD FT ≡ Mode 4 only; the top width at any section j in the transition corresponding to DEPTH, ft

TAU LB/SQ. FT. ≡ Modes 2 and 3 only; the maximum tractive stress at any section j in the transition, lb/ft^2

TAUO LB/SQ. FT. ≡ Mode 4 only; the average tractive stress at any section j in the transition. The maximum tractive stress cannot be obtained, because the value of C_{Tb} or C_{TS} is unknown for trapezoidal cross sections having unequal side slopes, lb/ft^2

VELOCITY FT/SEC ≡ The velocity at any section j of the transition, ft/sec

FRIC SLOPE FT/FT ≡ The instantaneous slope of the energy grade line at any section j, ft/ft

The symbols used for output for the prismatic channel are:

D50U $\equiv$ The D_{50} size of riprap used in the design of riprap structure, ft

CSU $\equiv \frac{SN}{SC} \equiv$ Ratio of bottom slope to critical slope used in the design of riprap structure

FSU $\equiv$ Factor of safety used in the design of riprap structure

BU $\equiv$ Bottom width of the prismatic channel, ft

ZU $\equiv$ Side slope of the prismatic channel, ft/ft

SN $\equiv$ Bottom slope of the prismatic channel, ft/ft

HN $\equiv$ Normal specific energy head corresponding to the design discharge, Q, in the prismatic channel, ft

DN $\equiv$ Depth of flow corresponding to the design discharge, Q, in the prismatic channel, ft

VN $\equiv$ Velocity at normal depth corresponding to the design discharge, Q, in the prismatic channel, ft/sec

RN $\equiv$ Hydraulic radius at normal depth in the prismatic channel, ft

SC $\equiv$ Critical slope corresponding to the design discharge, Q, in the prismatic channel, ft/ft

HC $\equiv$ Critical specific energy head corresponding to the design discharge, Q, in the prismatic channel, ft

DC $\equiv$ Critical depth corresponding to the design discharge, Q, in the prismatic channel, ft

N $= CN(D50U)^{EXPN} \equiv$ Manning's coefficient of roughness

K $\equiv$ Ratio of critical tractive stress on side slope to critical tractive stress on bottom of the trapezoidal channel

KPS $= \frac{p_n}{s_n} \equiv$ Ratio of wetted perimeter to bottom slope of the prismatic channel

CTAUB $\equiv$ A coefficient used to determine the maximum tractive stress along the boundary of the riprap lining on the bottom of the prismatic channel

TAUBM $= (CTAUB)(\gamma)(RN)(SN) \equiv$ The maximum tractive stress along the riprap lining on the bottom of the prismatic channel, lb/ft^2

TAUBA $= \frac{C50 \times D50U}{FSU} \equiv$ The allowable tractive stress for the riprap lining on the bottom of the prismatic channel, lb/ft^2

CTAUS $\equiv$ A coefficient used to determine the maximum tractive stress along the boundary of the riprap lining on the side slope of the prismatic channel

TAUSM $= (CTAUS)(\gamma)(RN)(SN) \equiv$ The maximum tractive stress along the riprap lining on the side slope of the prismatic channel, lb/ft^2

TAUSA $= K \frac{C50 \times D50U}{FSU} \equiv$ The allowable tractive stress for the riprap lining on the side slope of the prismatic channel, lb/ft^2

Messages

When the computer detects an input error, it prints out a message containing an error code. No computations are attempted for this design. The error codes are as follows:

Code 1 ≡ Value of 7th field of line 1 is not zero or blank

Code 2 ≡ $C50 < 0$

Code 3 ≡ $FS < 0$ or $0 < FS < 1.0$

Code 4 ≡ $CS < 0$

Code 5 ≡ $THETA < 20^{\circ}$

Code 6 ≡ $CN < 0$

Code 8 ≡ $EXPN < 0$

Code 9 ≡ $H < 0$

Code 10 ≡ $BS < 0$

Code 11 ≡ $DS < 0$

Code 12 ≡ $VS < 0$

Code 13 ≡ BS, DS, H are all zero or blank

Code 14 ≡ DS, VS, H are all zero or blank

Code 15 ≡ BS, DS, VS are all zero or blank

Code 16 ≡ BS, VS, H are all zero or blank

Code 17 ≡ BS, DS, H are all specified

Code 18 ≡ DS, VS, H are all specified

Code 19 ≡ BS, VS, H are all specified

Code 20 ≡ BS, DS, VS are all specified

Code 21 ≡ H = 0.0 or blank when design mode = 1.0

Code 22 ≡ $Q \leq 0$

Code 23 ≡ $ZU \leq 1.0$

Code 24 ≡ $ZS \leq 0$

Code 25 ≡ $CONV < 0$

Code 26 ≡ $DIV < 0$

Code 27 ≡ Value of 7th field of line 1 is not zero or blank

Code 28 ≡ Design mode is not 1.0, 2.0, 3.0, or 4.0

Code 29 ≡ $D50 < 0$

Code 30 ≡ $DS \geq H$

Code 31 ≡ $CS > 0.7$

Code 32 ≡ $CONV < 1.0$

Code 33 ≡ $DIV < 4.0$

Code 34 ≡ $(VS)^2/2g \geq H, \therefore DS \leq 0$

Code 35 ≡ $ZL \leq 0$

Code 36 ≡ $ZR \leq 0$

Code 44 ≡ The value of $\frac{\sin^2(\cot^{-1} z)}{\sin^2 \theta} \geq 1.0$, see equation (22)

Example No. 1

Given:

Design discharge, Q = 2500 cfs
Side slopes, ZU = 3.0
Specific energy head, H = 6.5 ft
Riprap size, D50 = 1.25 ft

Required:

Design a riprap trapezoidal channel having the steepest stable bottom slope consistent with the above conditions.

Solution:

The design obtained from the computer using mode 1 is as follows:

```
===========================================================================
   DESIGN OF RIPRAP PRISMATIC CHANNEL FOR A CONSTANT SPECIFIC ENERGY HEAD

       SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
                                    FOR
                            EXAMPLE DESIGN NO. 1
                              JANUARY 23, 1976

CAUTION--THE SPECIFIED D50= 1.250 FT EXCEEDS THE EXPERIMENTAL DATA SHOWN IN
REPORT 108.  HOWEVER, THE SPECIFIED D50 WILL BE USED AS THE ALLOWABLE D50.

            DIMENSIONS AND PARAMETERS OF THE RIPRAP CHANNEL

     Q= 2500.00 CFS        H=  6.500 FT        ZU=  3.00 FT/FT

    ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

    D50=  1.250 FT          CS= 0.7000          THETA= 35.0 DEGREES
    C50=  4.00 LB/CU.FT.    CN= 0.0395
     FS=  1.250           EXPN=  0.1667

FOR D50= 1.250 FT THE COMPUTED VALUE OF CS=0.7371 IS GREATER THAN THE ALLOWABLE
CS.  SOLUTION FOR D50 WILL BE MADE USING THE ALLOWABLE VALUE CS=0.7000

       DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL

  D50U=    1.176 FT    SN= 0.011279    SC= 0.016113   CTAUB =   1.335
   CSU=    0.7000      HN= 6.500 FT    HC= 6.429 FT    TAUBM=   3.602 LB/SQ.FT.
   FSU=    1.25        DN= 5.090 FT    DC= 4.619 FT    TAUBA=   3.764 LB/SQ.FT.
    BU=   36.30   FT   VN= 9.52 FPS     N= 0.0406     CTAUS =   1.164
    ZU=    3.00        RN= 3.83 FT      K= 0.8343      TAUSM=   3.141 LB/SQ.FT.
                                      KPS= 6.07E+03    TAUSA=   3.141 LB/SQ.FT.
===========================================================================
```

Observe that the last output message indicates why the D50 = 1.25 ft riprap cannot be used in the design. Also observe that, although the maximum tractive stress occurs on the bottom of the channel, the controlling tractive stress occurs on the side slopes of the channel.

Example No. 2

Given:

Design discharge, Q = 2750 cfs
Side slopes, ZU = 2.5 and ZS = 3.0
Riprap size, D50 = 1.0 ft
Bottom width, BS = 100.0 ft
Starting depth, DS = 7.0 ft
Factor of safety, FS = 1.25

Required:

Design a riprap structure and determine the length of the structure if the total vertical drop desired for gradient control is 6.0 ft.

Solution:

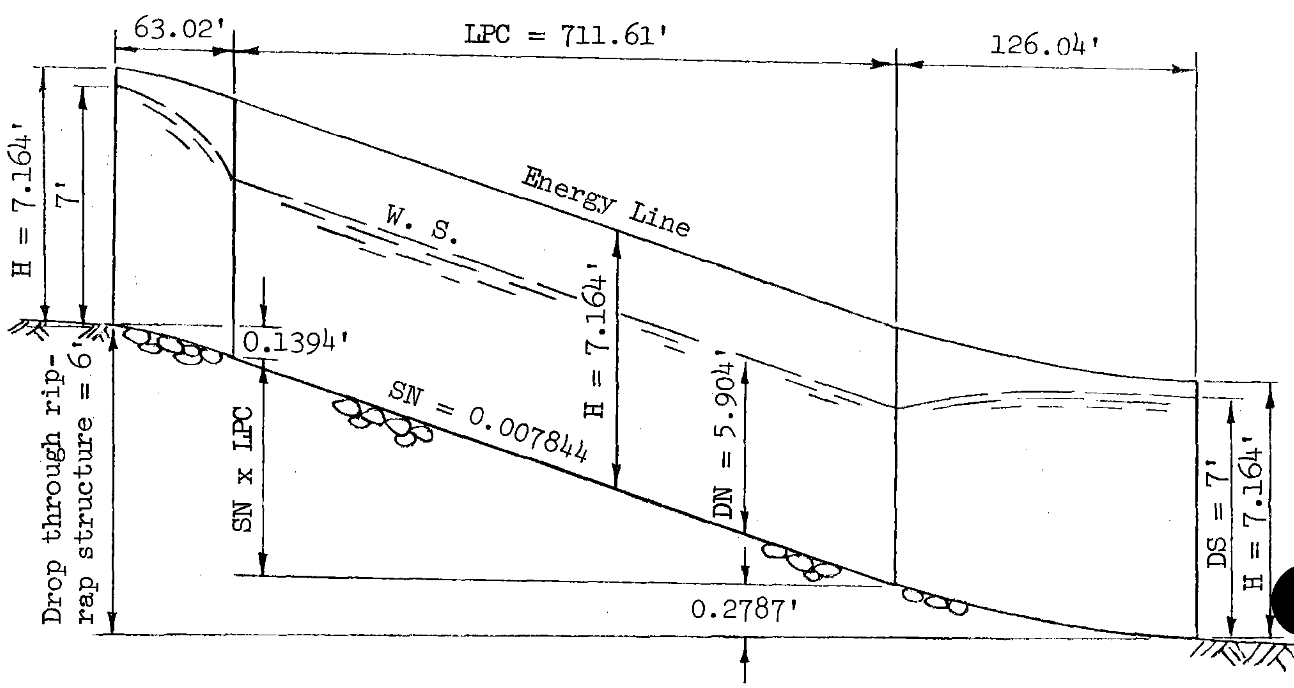
The design obtained from the computer using mode 2 is given on the next page.

The vertical drop in the prismatic channel is equal to the drop through the riprap structure minus the vertical drop contained in both transitions. The length of the prismatic channel, LPC, is equal to the vertical drop in the prismatic channel divided by the bottom slope of the prismatic channel, or

$$\text{LPC} = \frac{6.0 - 0.2787 - 0.1394}{0.007844} = 711.61 \text{ ft}$$

The total length of the structure is equal to the length of the prismatic channel plus the lengths of both transitions or

the total length = 711.61 + 126.04 + 63.02 = 900.67 ft



ELEVATION

DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 2
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS	H= 7.164 FT	ZS= 3.00 FT/FT
BS= 100.000 FT	DS= 7.000 FT	VS= 3.247 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT	CS= 0.7000	THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT.	CN= 0.0395	CONV= 2.000
FS= 1.250	EXPN= 0.1667	DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	3.00	7.000	0.278	3.247	7.03E-04
12.60	0.0095	93.70	2.95	6.979	0.322	3.448	8.03E-04
25.21	0.0204	87.40	2.90	6.954	0.377	3.677	9.27E-04
37.81	0.0331	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.0480	74.79	2.80	6.883	0.533	4.247	1.28E-03
63.02	0.0658	68.49	2.75	6.833	0.646	4.611	1.55E-03
75.62	0.0876	62.19	2.70	6.767	0.799	5.051	1.91E-03
88.23	0.1150	55.89	2.65	6.677	1.011	5.598	2.43E-03
100.83	0.1507	49.58	2.60	6.545	1.325	6.309	3.23E-03
113.44	0.2002	43.28	2.55	6.334	1.838	7.305	4.62E-03
126.04	0.2787	36.98	2.50	5.904	2.910	9.003	7.84E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 1.000 FT	SN= 0.007844	SC= 0.014965	CTAUB = 1.339
CSU= 0.5242	HN= 7.164 FT	HC= 6.920 FT	TAUBM= 2.910 LB/SQ.FT.
FSU= 1.25	DN= 5.904 FT	DC= 4.943 FT	TAUBA= 3.200 LB/SQ.FT.
BU= 36.98 FT	VN= 9.00 FPS	N= 0.0395	CTAUS = 1.122
ZU= 2.50	RN= 4.44 FT	K= 0.7621	TAUSM= 2.439 LB/SQ.FT.
		KPS= 8.77E+03	TAUSA= 2.439 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	36.98	2.50	5.904	2.910	9.003	7.84E-03
6.30	0.0393	43.28	2.55	6.334	1.838	7.305	4.62E-03
12.60	0.0640	49.58	2.60	6.545	1.325	6.309	3.23E-03
18.91	0.0819	55.89	2.65	6.677	1.011	5.598	2.43E-03
25.21	0.0955	62.19	2.70	6.767	0.799	5.051	1.91E-03
31.51	0.1064	68.49	2.75	6.833	0.646	4.611	1.55E-03
37.81	0.1154	74.79	2.80	6.883	0.533	4.247	1.28E-03
44.11	0.1228	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.1292	87.40	2.90	6.954	0.377	3.677	9.27E-04
56.72	0.1346	93.70	2.95	6.979	0.322	3.448	8.03E-04
63.02	0.1394	100.00	3.00	7.000	0.278	3.247	7.03E-04

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.15 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.05 FT

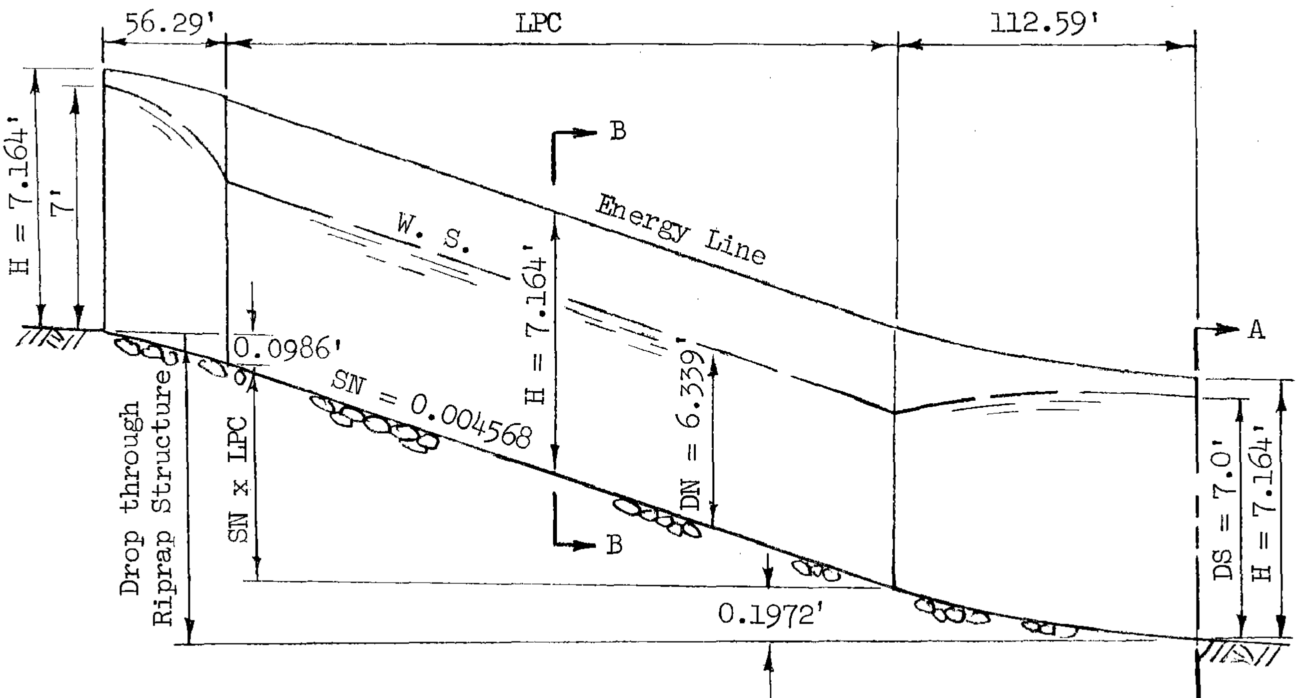
Example No. 3

Given:
Design discharge, Q = 2750 cfs
Side slopes, ZU = 2.5, ZS = 3.0
Riprap size, D50 = 1.0 ft
Bottom width, BS = 100.0 ft
Starting depth, DS = 7.0 ft
Factor of safety, FS = 2.0
Value of CS = 0.6

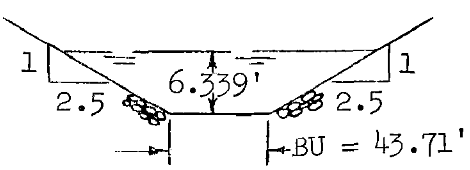
Note that the given parameters for this example are the same as Example No. 2 except for FS and CS values.

Required:
Design the riprap structure.

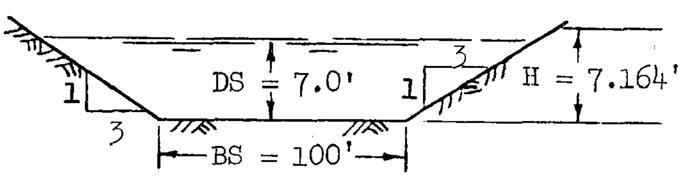
Solution:
The design obtained from the computer using mode 3 is given on the next page. Observe, although the value of CS was specified, it was not used in the design since CSU < CS.



ELEVATION



SECTION B-B



SECTION A-A

DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 3
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS	H= 7.164 FT	ZS= 3.00 FT/FT
BS= 100.000 FT	DS= 7.000 FT	VS= 3.247 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT	CS= 0.6000	THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT.	CN= 0.0395	CONV= 2.000
FS= 2.000	EXPN= 0.1667	DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	3.00	7.000	0.278	3.247	7.03E-04
11.26	0.0084	94.37	2.95	6.981	0.317	3.426	7.92E-04
22.52	0.0179	88.74	2.90	6.959	0.365	3.628	8.99E-04
33.78	0.0288	83.11	2.85	6.933	0.423	3.856	1.03E-03
45.03	0.0413	77.48	2.80	6.900	0.494	4.117	1.19E-03
56.29	0.0559	71.85	2.75	6.860	0.584	4.419	1.40E-03
67.55	0.0732	66.22	2.70	6.810	0.699	4.773	1.67E-03
78.81	0.0941	60.59	2.65	6.744	0.850	5.197	2.04E-03
90.07	0.1199	54.97	2.60	6.656	1.057	5.717	2.55E-03
101.33	0.1529	49.34	2.55	6.531	1.354	6.381	3.31E-03
112.59	0.1972	43.71	2.50	6.339	1.819	7.285	4.57E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 1.000 FT	SN= 0.004568	SC= 0.015123	CTAUB = 1.316
CSU= 0.3020	HN= 7.164 FT	HC= 6.422 FT	TAUBM= 1.819 LB/SQ.FT.
FSU= 2.00	DN= 6.339 FT	DC= 4.540 FT	TAUBA= 2.000 LB/SQ.FT.
BU= 43.71 FT	VN= 7.28 FPS	N= 0.0395	CTAUS = 1.103
ZU= 2.50	RN= 4.85 FT	K= 0.7621	TAUSM= 1.524 LB/SQ.FT.
		KPS= 1.70E+04	TAUSA= 1.524 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	43.71	2.50	6.339	1.819	7.285	4.57E-03
5.63	0.0222	49.34	2.55	6.531	1.354	6.381	3.31E-03
11.26	0.0387	54.97	2.60	6.656	1.057	5.717	2.55E-03
16.89	0.0515	60.59	2.65	6.744	0.850	5.197	2.04E-03
22.52	0.0620	66.22	2.70	6.810	0.699	4.773	1.67E-03
28.15	0.0706	71.85	2.75	6.860	0.584	4.419	1.40E-03
33.78	0.0779	77.48	2.80	6.900	0.494	4.117	1.19E-03
39.41	0.0842	83.11	2.85	6.933	0.423	3.856	1.03E-03
45.03	0.0896	88.74	2.90	6.959	0.365	3.628	8.99E-04
50.66	0.0944	94.37	2.95	6.981	0.317	3.426	7.92E-04
56.29	0.0986	100.00	3.00	7.000	0.278	3.247	7.03E-04

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.08 FT

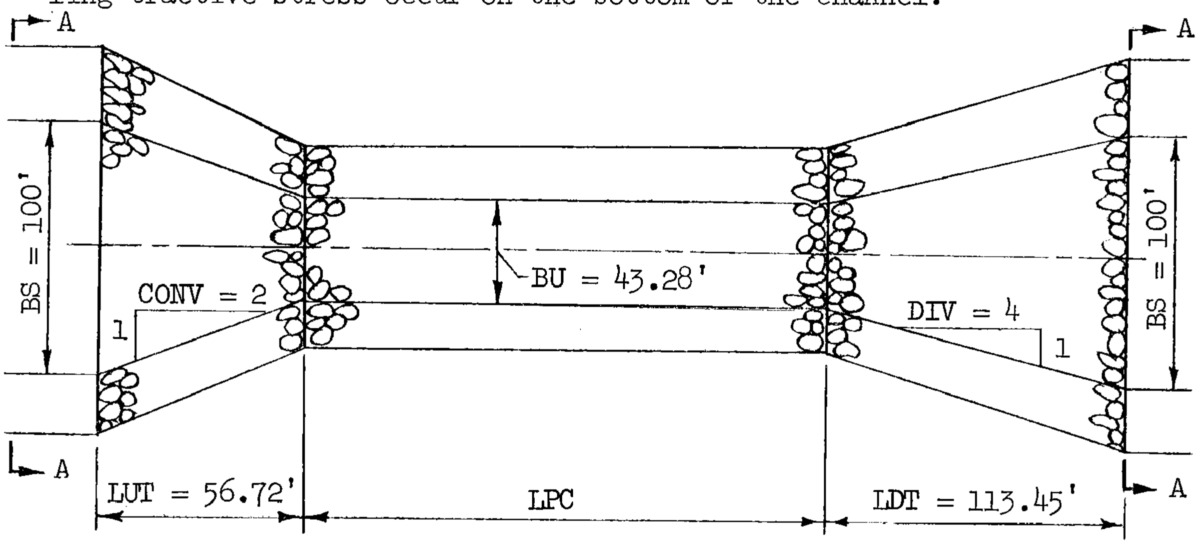
THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.03 FT

Example No. 4

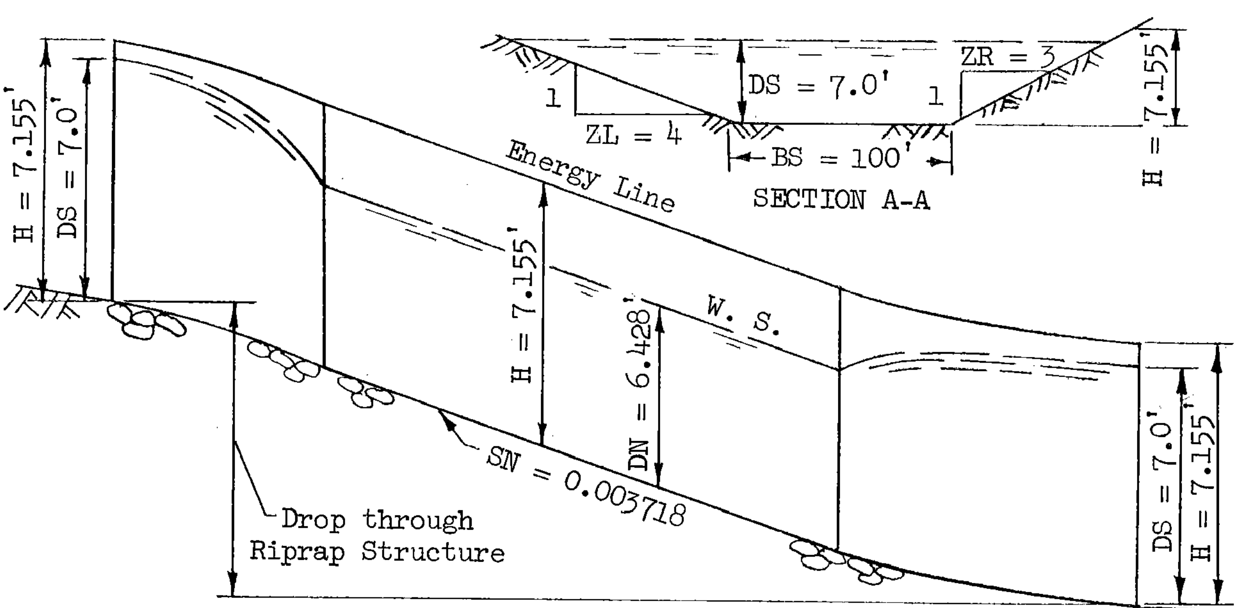
Given:
Design discharge, Q = 2750 cfs
Side slopes, ZU = 3.0, ZL = 4.0, and ZR = 3.0
Riprap size, D50 = 0.75 ft
Bottom width, BS = 100.0 ft
Starting depth, DS = 7.0 ft
Rate of convergence, CONV = 2.0
Factor of safety, FS = 2.0
Angle of repose, THETA = 42°

Required:
Design a riprap structure where the adjoining channels have side slopes ZL = 4.0 and ZR = 3.0 (See SECTION A-A).

Solution:
The design obtained from the computer using mode 4 is given on the next page and the dimensions and parameters are outlined in the sketch below. Observe that both the maximum tractive stress and the controlling tractive stress occur on the bottom of the channel.



PLAN



ELEVATION

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DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 4
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

	Q= 2750.00 CFS	
ZL= 4.000	DS= 7.000 FT	H= 7.155 FT
ZR= 3.000	BS=100.000 FT	VS= 3.155 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 0.750 FT	CS= 0.7000	THETA= 42.0 DEGREES
C50= 4.00 LB/CU.FT.	CN= 0.0395	CONV= 2.000
FS= 2.000	EXPN= 0.1667	DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZLT	ZRT	DEPTH FT	TOP WD FT	TAUO LB/SQ.FT.	VEL. FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	4.00	3.00	7.000	149.00	0.222	3.155	6.17E-04
11.34	0.01	94.33	3.90	3.00	6.983	142.51	0.248	3.326	6.94E-04
22.69	0.02	88.66	3.80	3.00	6.963	136.00	0.278	3.516	7.86E-04
34.03	0.03	82.98	3.70	3.00	6.938	129.47	0.314	3.731	8.98E-04
45.38	0.04	77.31	3.60	3.00	6.909	122.91	0.358	3.976	1.04E-03
56.72	0.05	71.64	3.50	3.00	6.873	116.31	0.413	4.258	1.21E-03
68.07	0.06	65.97	3.40	3.00	6.828	109.66	0.481	4.587	1.44E-03
79.41	0.08	60.29	3.30	3.00	6.770	102.94	0.571	4.977	1.74E-03
90.76	0.10	54.62	3.20	3.00	6.693	96.12	0.690	5.452	2.15E-03
102.10	0.13	48.95	3.10	3.00	6.586	89.12	0.858	6.048	2.76E-03
113.45	0.17	43.28	3.00	3.00	6.428	81.84	1.111	6.839	3.72E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 0.750 FT	SN= 0.003718	SC= 0.013810	CTAUB = 1.350
CSU= 0.2692	HN= 7.155 FT	HC= 6.301 FT	TAUBM= 1.500 LB/SQ.FT.
FSU= 2.00	DN= 6.428 FT	DC= 4.488 FT	TAUBA= 1.500 LB/SQ.FT.
BU= 43.28 FT	VN= 6.84 FPS	N= 0.0377	CTAUS = 1.177
ZU= 3.00	RN= 4.79 FT	K= 0.8813	TAUSM= 1.308 LB/SQ.FT.
		KPS= 2.26E+04	TAUSA= 1.322 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	ZLT	ZRT	DEPTH FT	TOP WD FT	TAUO LB/SQ.FT.	VEL. FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	43.28	3.00	3.00	6.428	81.84	1.111	6.839	3.72E-03
5.67	0.02	48.95	3.10	3.00	6.586	89.12	0.858	6.048	2.76E-03
11.34	0.03	54.62	3.20	3.00	6.693	96.12	0.690	5.452	2.15E-03
17.02	0.04	60.29	3.30	3.00	6.770	102.94	0.571	4.977	1.74E-03
22.69	0.05	65.97	3.40	3.00	6.828	109.66	0.481	4.587	1.44E-03
28.36	0.06	71.64	3.50	3.00	6.873	116.31	0.413	4.258	1.21E-03
34.03	0.07	77.31	3.60	3.00	6.909	122.91	0.358	3.976	1.04E-03
39.71	0.07	82.98	3.70	3.00	6.938	129.47	0.314	3.731	8.98E-04
45.38	0.08	88.66	3.80	3.00	6.963	136.00	0.278	3.516	7.86E-04
51.05	0.08	94.33	3.90	3.00	6.983	142.51	0.248	3.326	6.94E-04
56.72	0.08	100.00	4.00	3.00	7.000	149.00	0.222	3.155	6.17E-04

==

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.06 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.03 FT

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Example No. 5

Given:

Design discharge, Q = 2750 cfs
Side slopes, ZU = 2.5, ZS = 3.0
Riprap size, D50 = 1.0 ft
Downstream bottom width, BS = 100.0 ft
Upstream bottom width, BS = 150.0 ft
Starting depth, DS = 7.0 ft
Factor of safety, FS = 1.25

Note that the given parameters of this example are the same as Example No. 2 except that the bottom width, BS, at the downstream end of the structure is not the same as the BS at the upstream end of the structure.

Required:

Design the riprap structure where the adjoining channels have different bottom widths.

Solution:

Since the bottom widths at the upstream end and downstream end of the structure are not equal, two design runs are required. The first design run is for BS = 100 ft. The second design run is for BS = 150 ft and it uses the same specific energy head, H, as was used in the first design run. The final design is composed of the following:

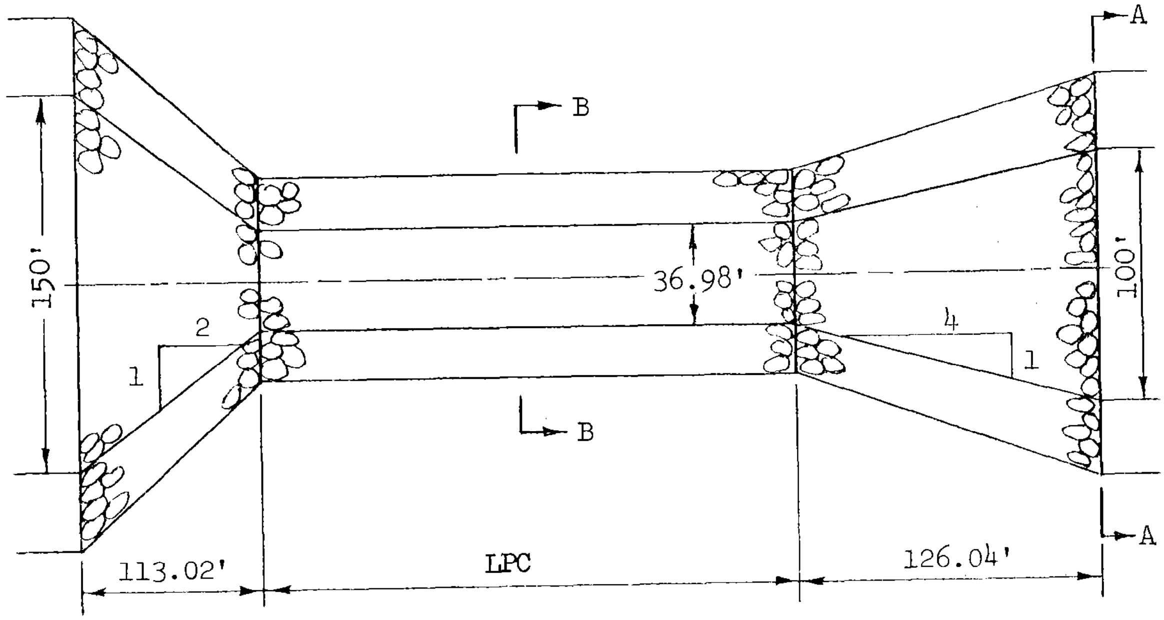
1. the design of the downstream transition from the first design run, i.e., for BS = 100 ft (The design of the upstream transition for this run is disregarded.)
2. the design of the prismatic channel from either design run (They are the same.)
3. the design of the upstream transition from the second design run, i.e., for BS = 150 ft (The design of the downstream transition for this run is disregarded.)

The composite design is given on the next three pages.

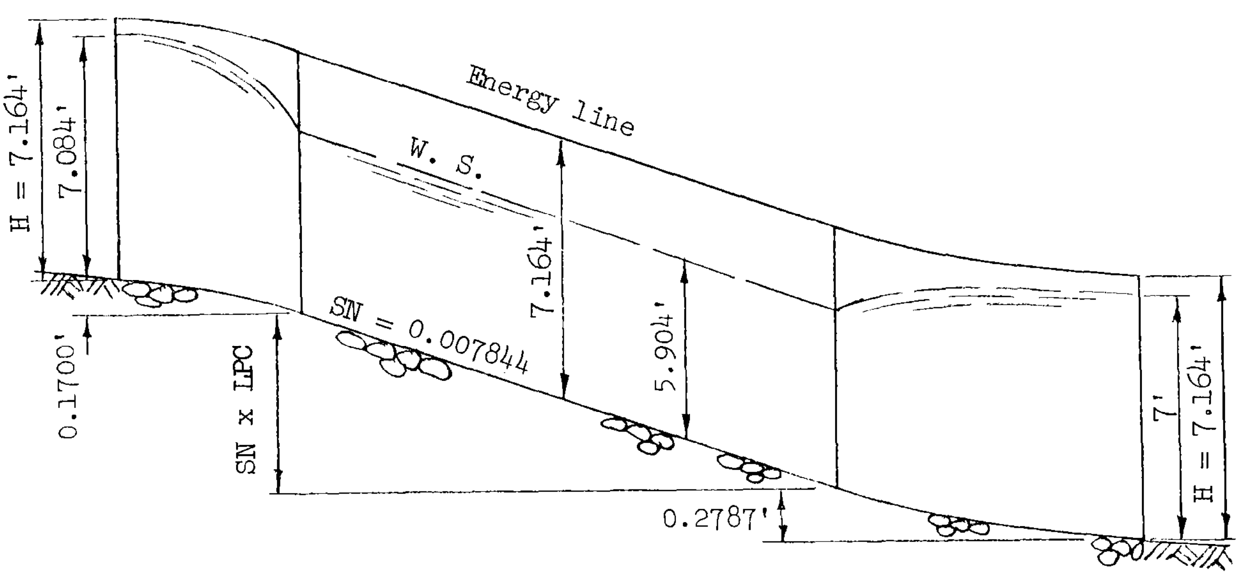
Observe that the depths at the ends of the structure are not equal. The larger depth occurs at the upstream end of the riprap structure because

1. the bottom width at the upstream end is larger than the bottom width at the downstream end and
2. the structure maintains a constant specific energy head at subcritical flow throughout the structure.

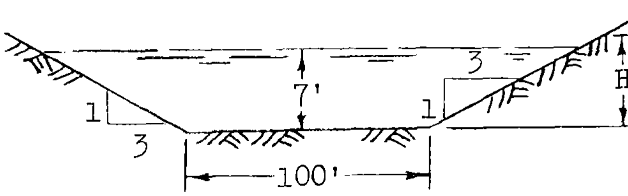
Since the depth at the upstream end is larger than the depth at the downstream end, the velocity at the upstream end is smaller than the velocity at the downstream end at constant specific energy head.



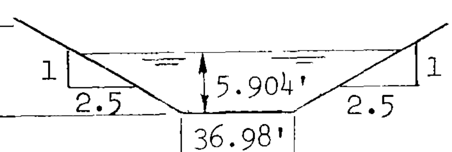
PLAN



ELEVATION



SECTION A-A



SECTION B-B

DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 5
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS	H= 7.164 FT	ZS= 3.00 FT/FT
BS= 100.000 FT	DS= 7.000 FT	VS= 3.247 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT	CS= 0.7000	THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT.	CN= 0.0395	CONV= 2.000
FS= 1.250	EXPN= 0.1667	DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	100.00	3.00	7.000	0.278	3.247	7.03E-04
12.60	0.0095	93.70	2.95	6.979	0.322	3.448	8.03E-04
25.21	0.0204	87.40	2.90	6.954	0.377	3.677	9.27E-04
37.81	0.0331	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.0480	74.79	2.80	6.883	0.533	4.247	1.28E-03
63.02	0.0658	68.49	2.75	6.833	0.646	4.611	1.55E-03
75.62	0.0876	62.19	2.70	6.767	0.799	5.051	1.91E-03
88.23	0.1150	55.89	2.65	6.677	1.011	5.598	2.43E-03
100.83	0.1507	49.58	2.60	6.545	1.325	6.309	3.23E-03
113.44	0.2002	43.28	2.55	6.334	1.838	7.305	4.62E-03
126.04	0.2787	36.98	2.50	5.904	2.910	9.003	7.84E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 1.000 FT	SN= 0.007844	SC= 0.014965	CTAUB = 1.339
CSU= 0.5242	HN= 7.164 FT	HC= 6.920 FT	TAUBM= 2.910 LB/SQ.FT.
FSU= 1.25	DN= 5.904 FT	DC= 4.943 FT	TAUBA= 3.200 LB/SQ.FT.
BU= 36.98 FT	VN= 9.00 FPS	N= 0.0395	CTAUS = 1.122
ZU= 2.50	RN= 4.44 FT	K= 0.7621	TAUSM= 2.439 LB/SQ.FT.
		KPS= 8.77E+03	TAUSA= 2.439 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	36.98	2.50	5.904	2.910	9.003	7.84E-03
6.30	0.0393	43.28	2.55	6.334	1.838	7.305	4.62E-03
12.60	0.0640	49.58	2.60	6.545	1.325	6.309	3.23E-03
18.91	0.0819	55.89	2.65	6.677	1.011	5.598	2.43E-03
25.21	0.0955	62.19	2.70	6.767	0.799	5.051	1.91E-03
31.51	0.1064	68.49	2.75	6.833	0.646	4.611	1.55E-03
37.81	0.1154	74.79	2.80	6.883	0.533	4.247	1.28E-03
44.11	0.1228	81.09	2.85	6.923	0.446	3.940	1.08E-03
50.42	0.1292	87.40	2.90	6.954	0.377	3.677	9.27E-04
56.72	0.1346	93.70	2.95	6.979	0.322	3.448	8.03E-04
63.02	0.1394	100.00	3.00	7.000	0.278	3.247	7.03E-04

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.15 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.05 FT

DESIGN OF RIPRAP GRADIENT CONTROL STRUCTURE
FOR A CONSTANT SPECIFIC ENERGY HEAD

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR
EXAMPLE DESIGN NO. 5
JANUARY 23, 1976

DIMENSIONS AND PARAMETERS UPSTREAM AND DOWNSTREAM OF THE RIPRAP STRUCTURE

Q= 2750.00 CFS	H= 7.164 FT	ZS= 3.00 FT/FT
BS= 150.000 FT	DS= 7.084 FT	VS= 2.267 FT/SEC

ADDITIONAL DESIGN PARAMETERS EITHER SPECIFIED OR OBTAINED BY DEFAULT

D50= 1.000 FT	CS= 0.7000	THETA= 35.0 DEGREES
C50= 4.00 LB/CU.FT.	CN= 0.0395	CONV= 2.000
FS= 1.250	EXPN= 0.1667	DIV= 4.000

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
DOWNSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	150.00	3.00	7.084	0.123	2.267	3.17E-04
22.60	0.0078	138.70	2.95	7.072	0.143	2.437	3.71E-04
45.21	0.0169	127.40	2.90	7.056	0.168	2.636	4.39E-04
67.81	0.0279	116.09	2.85	7.036	0.200	2.871	5.29E-04
90.42	0.0412	104.79	2.80	7.009	0.252	3.153	6.51E-04
113.02	0.0579	93.49	2.75	6.974	0.328	3.500	8.21E-04
135.63	0.0792	82.19	2.70	6.923	0.439	3.938	1.07E-03
158.23	0.1078	70.89	2.65	6.848	0.608	4.511	1.46E-03
180.83	0.1484	59.58	2.60	6.727	0.888	5.305	2.13E-03
203.44	0.2119	48.28	2.55	6.503	1.422	6.519	3.49E-03
226.04	0.3399	36.98	2.50	5.904	2.910	9.003	7.84E-03

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE PRISMATIC CHANNEL
OF THE RIPRAP STRUCTURE

D50U= 1.000 FT	SN= 0.007844	SC= 0.014966	CTAUB = 1.339
CSU= 0.5242	HN= 7.164 FT	HC= 6.920 FT	TAUBM= 2.910 LB/SQ.FT.
FSU= 1.25	DN= 5.904 FT	DC= 4.943 FT	TAUBA= 3.200 LB/SQ.FT.
BU= 36.98 FT	VN= 9.00 FPS	N= 0.0395	CTAUS = 1.122
ZU= 2.50	RN= 4.44 FT	K= 0.7621	TAUSM= 2.439 LB/SQ.FT.
		KPS= 8.77E+03	TAUSA= 2.439 LB/SQ.FT.

DIMENSIONS AND PARAMETERS ASSOCIATED WITH THE TRANSITION AT THE
UPSTREAM END OF THE RIPRAP PRISMATIC CHANNEL

LENGTH FT	RISE FT	WIDTH FT	Z	DEPTH FT	TAU LB/SQ.FT.	VELOCITY FT/SEC	FRIC SLOPE FT/FT
0.0	0.0	36.98	2.50	5.904	2.910	9.003	7.84E-03
11.30	0.0640	48.28	2.55	6.503	1.422	6.519	3.49E-03
22.60	0.0958	59.58	2.60	6.727	0.888	5.305	2.13E-03
33.91	0.1161	70.88	2.65	6.848	0.608	4.511	1.46E-03
45.21	0.1304	82.19	2.70	6.923	0.439	3.938	1.07E-03
56.51	0.1410	93.49	2.75	6.974	0.328	3.500	8.21E-04
67.81	0.1494	104.79	2.80	7.009	0.252	3.153	6.51E-04
79.11	0.1560	116.09	2.85	7.036	0.200	2.871	5.29E-04
90.42	0.1615	127.40	2.90	7.056	0.168	2.636	4.39E-04
101.72	0.1661	138.70	2.95	7.072	0.143	2.437	3.71E-04
113.02	0.1700	150.00	3.00	7.084	0.123	2.267	3.17E-04

TRANSITION CONVERSION LOSSES

THE CONVERSION LOSS IN THE DOWNSTREAM TRANSITION MAY BE AS MUCH AS 0.21 FT

THE CONVERSION LOSS IN THE UPSTREAM TRANSITION MAY BE AS MUCH AS 0.05 FT

*U.S. GOVERNMENT PRINTING OFFICE: 1978 0-280-930/SCS-326